Acquisition Directorate
Research & Development Center

Report No. CG-D-04-15

Alternatives to Pyrotechnic Distress Signals; Laboratory and Field Studies

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March 2015

Homeland Security

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Technical Report Documentation Page

1. Report No. CG-D-04-15	2. Government Accession Number	3. Recipient's Catalog No.
4. Title and Subtitle Alternatives to Pyrotechnic Distress Signals; Laboratory and Field Studies		5. Report Date March 2015 6. Performing Organization Code Project No. 1101
7. Author(s) M. J. Lewandowski, A. M. Rothblum, V. A. Reubelt, T. L. Amerson, S. A. Balk, W. A. Perez, L. D. Elam		8. Performing Report No. UDI # 1114
9. Performing Organization Name and Address U.S. Coast Guard Research and Development Center 1 Chelsea Street New London, CT 06320		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Organization Name and Address U. S. Department of Homeland Security Commandant (CG-ENG, CG-SAR, CG-BSX) U. S. Coast Guard 2703 Martin Luther King Jr. Ave. SE Washington, DC 20593-7363		13. Type of Report & Period Covered Final Report 14. Sponsoring Agency Code Commandant (CG-ENG-4) U. S. Coast Guard Headquarters Washington, DC

15. Supplementary Notes

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16. Abstract (MAXIMUM 200 WORDS)

This report documents a multi-year project effort to develop a specification for a light-emitting diode (LED) signal characteristic as an alternative to pyrotechnic, maritime distress signal flares as visual distress signals. The report includes the methodology used in evaluating color, flash pattern, and intensity for an LED distress signal, conspicuous against certain lighting conditions, at six nautical miles, in 10 miles meteorological visibility.

The effort included a literature review, measurement and quantifying different levels of background lighting to recreate their effect in a vision laboratory, a series of laboratory tests to determine signal conspicuity in a controlled environment, and a field test in the marine environment.

The human-subject laboratory experiments determined relative LED signal conspicuity, based on subjects' accurate identification of a signal and the response time to make that identification. The lab results (conspicuous signal characteristics) were the basis for field testing.

In addition to LED signals, the human-subject field test included two, commercial, off-the-shelf (COTS) signal devices and a handheld pyrotechnic flare in the signal evaluation. In four nights of testing, the experimenters produced a signal characteristic that was significantly more conspicuous than the flare and the two COTS devices.

17. Key Words Visual Distress Signal Device (VDSD), Light Emitting Diode (LED), characteristic, effective intensity, color, flash pattern, response time, conspicuity	18. Distribution Statement Distribution Statement A: Approved for public release; distribution is unlimited.

19. Security Class (This Report) UNCLAS//Public	20. Security Class (This Page) UNCLAS//Public	21. No of Pages 82	22. Price

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ACKNOWLEDGEMENTS

The project team is grateful for the support of Coast Guard Station Sandy Hook, NJ and the U. S. National Park Service, Gateway National Recreation Area, Sandy Hook staff during measurements for the analysis of the nighttime maritime background environment, Fall 2013.

The project team is also grateful to the command and crew of Coast Guard Station Eatons Neck, NY, for the unhesitating support, understanding, and patience in allowing the project access to their facility and services during the September 2014 field testing.

Special recognition goes to the Coast Guard Auxiliarists and members of the U. S. Power Squadrons who tolerated delays, insects, and the evening chill for up to four nights to serve as test subjects in the field study. The project team acknowledges the behind-the-scenes efforts of the First Coast Guard District and Sector Long Island Sound Auxiliary Affairs Officers and the Sector Long Island Sound Auxiliary Coordinator to insure participation of a large pool of individuals.

The project also recognizes the members of the R&D Center staff for their administrative and logistical support, and finally, the enthusiastic participation of the ad hoc field experiment team that developed and applied innovative methods, both in preparation for and during field testing.

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EXECUTIVE SUMMARY

The Coast Guard Research & Development Center executed a multi-year effort to develop a specification for a light-emitting diode (LED) signal characteristic that could be an alternative to pyrotechnic, maritime distress signal flares as visual distress signals. Though manufacturers currently market LED and laser devices that may be effective to some degree, this report documents a rigorous methodology used to develop a characteristic (color, flash pattern, and intensity) for an LED distress signal that will be conspicuous against certain lighting conditions at six nautical miles, in 10 miles meteorological visibility.

The project reviewed previous work, and relied to a large extent on studies to improve maritime aids to navigation signals, where researchers dealt with the same primary issues: visibility of a light signal, conspicuity against complex backgrounds, and effective signal intensity. The project also quantified four different levels of background lighting to recreate their effect in a vision laboratory, and for reference in additional studies.

Because there could be countless combinations of LED colors and flash patterns, the project designed and conducted laboratory experiments to reduce the number of possible signal characteristic combinations for evaluation. These human-subject laboratory experiments ranked relative signal conspicuity, based on subjects' accurate identification of a signal and their response time to make that identification. The lab results were the basis for field testing to make sure that what worked in the lab worked in the real world.

The laboratory testing included "sparse" and "moderate" background lighting conditions, against which the subjects identified the signals. However, due to the difficulty in designing the real-world field test to provide sufficient trials for each signal, but not overly tax volunteer subjects, and allow experiment conduct within budget and schedule, the project team conducted the field test only against "sparse" background lighting conditions.

The field test validated the laboratory results for some of the characteristic elements. Also, the field test included two, commercial off-the-shelf (COTS) signal devices and a handheld pyrotechnic flare in the signal evaluation. Over four nights of testing, the project built on the information learned in the lab and produced a signal characteristic that was significantly more conspicuous than a hand-held red pyrotechnic flare, and two COTS devices.

The project recommends that the signal characteristic, a 4 Hertz flashing, group alternating, cyan and red-orange signal, be incorporated into the specification of an LED device as an alternative to a red, hand-held flare, acceptable for U. S. domestic vessel equipment carriage requirements. However, since U. S. Coast Guard rescue aircraft normally conduct nighttime searches using night vision imaging systems (NVIS) with "minus-blue" filtering," the project recommends additional research and testing leading to the inclusion, if necessary, of an additional flashing signal closer to the NVIS central response range, approximately 750-800 nanometers.

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

aH	Amp Hours
alt	Alternating
AtoN	Aid(s) to navigation
AWL	Above waterline / above water level
Bl	Blue
cd	Candela
cd/m^2	Candela per square meter
CFR	Code of Federal Regulations
CG	Coast Guard
CIE	International Commission of Illumination (Commisison Internationale de l'Eclairage)
COLREGS	International Regulations for Prevention of Collisions at Sea
COTS	Commercial off-the-shelf
Cy	Cyan
Deg F	Degrees Fahrenheit
Dist	Distance
EaN	Eatons Neck
EFI	Equivalent fixed intensity
EPIRB	Emergency position-indicating radio beacon
fl	Flashes / flashing
ft	Foot / feet
G	Green
Gru	Group
Hbr Sta	Harbor Station (power plant)
hr	Hour
Hz	Hertz (cycles per second)
IALA	International Association of Marine Aids to Navigation and Lighthouse Authorities
in	Inch
Int	Interrupt
IRB	Institutional Review Board
^oK	Degrees Kelvin
kts	Knots
Lat	Latitude
LED	Light-emitting diode
LIS	Long Island Sound
lm	Lumens
lon	Longitude
Lt	Light
lx	Lux
M	Magnetic bearing
mrad	Milliradian (1/1000 radian or 0.057 degrees)
ms	Millisecond
mW	Milliwatt

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

N	North
NM	Nautical mile
nm	Nanometer (1 x 10^{-9} meter)
NOS	National Ocean Service
NSMRL	Naval Submarine Medical Research Lab
Or	Orange
p	Probability
Pt	Point
PWM	Pulse width modulation
R	Red
RDC	Research and Development Center
R-Or	Red-orange
RT	Response time
SAIC	Science Applications International Corporation
SAR	Search and rescue
sec	Seconds
SOLAS	Safety of Life at Sea
SOS (S-O-S)	Distress signal in Morse Code
USAF	U.S. Air Force
V	Volts
VDSD	Visual distress signal device
Vsl	Vessel
W	West (in App. B)
W	White (signal color)
WS	Wind speed

1 INTRODUCTION

Mariners have long relied on devices to let others know of a distress (the "notification" phase), and to help responders get close enough to the distressed vessel or victims in the water to actually provide assistance (the "locate" phase). A single device might not be suitable for both uses.

There are many different approaches to accomplishing distress notification and location, including signal flags, pyrotechnic devices (meteor and hand-held flares and smoke-markers), and electronic means such as radios and Emergency Position-Indicating Radio Beacons (EPIRBs). Vessels (primarily commercial) must comply with a number of distress notification carriage requirements, depending on the type of commerce, area of operations, participation in international protocols, and other factors. There are no Federal requirements for recreational vessels to carry radios; however, they are required to carry visual and audible distress signal devices. Beyond the mandated carriage requirements, vessels and boats may also carry other distress signals voluntarily.

One required visual distress signal device (VDSD) is the pyrotechnic flare. Although widely used, pyrotechnic devices present certain hazards and drawbacks for use, storage, and disposal. For instance, pyrotechnic flares can injure the user or a bystander, or start a fire on a vessel. The use of perchlorates, a chemical compound in many flares has become increasingly suspect due to health concerns related to their ability to act as an iodine mimic within biological systems and interfere with normal thyroid function, especially in infants (Young, et al., 2011). Because flares are considered hazardous materials, they also present storage and disposal concerns. Since flares have expiration dates, mariners face the quandary of not using them except for actual distress, but not having a relatively easy way to dispose of them legally.

The most significant issue about the use of pyrotechnic flares is their effectiveness. During the lead-up to this project in 2011, analysts reviewed search and rescue (SAR) data. From the period 2003-2010, fewer than 4% of SAR notifications were by visual means, and of those, only 17% were by pyrotechnics, less than 1% of the total notifications. Of these approximately 1400 notifications over 8 years, less than 20% of those cases were successfully resolved. The bulk of the "flare sighting" cases had no resolution. (For the most part, this is due to reporting sources mis-identifying other phenomenon such as aircraft, celestial events, or fires on shore as "flare-sightings.")

For these reasons, the Coast Guard's (CG) Office of Search and Rescue requested the CG Research and Development Center (RDC) to investigate alternatives to pyrotechnic flares.

At the same time, the CG's Lifesaving and Fire Safety Standards Division and Boating Safety Division were receiving input from equipment manufacturers and potential users that light-emitting diode (LED) devices were capable of displaying a potential equivalent to a distress signal, but there were no standards for this type of device. These two offices requested RDC to determine the appropriate criteria for the evaluation of LED devices as maritime distress signals.

In March 2011, the RDC held a workshop (U.S. Coast Guard Research & Development Center, 29-30 March 2011) to determine functional requirements for VDSDs. Using the requirements developed at the workshop, the RDC conducted market research and procured for testing, devices that use various types of light sources for examination in a 2011 study. This 2011 study took the group of signals, roughly compared visual effectiveness at distances ≤ 5 nautical miles (NM), and identified the signal characteristics (color,

flash pattern, and perceived brightness) that differentiated how detectable and attention-getting the signals were. The 2011 study included lab testing to obtain photometric data to understand the physical (beam width, peak intensity, temporal characteristics, etc.) and perceptual (color, effective intensity) aspects of these signal devices; and to use those data to select a subset of devices for field evaluation.

RDC's objective throughout the testing was to identify characteristics of high-performing devices to support eventual development of performance requirements for future distress signals, as opposed to picking the best device. The results showed that the most effective signals had the highest effective intensities. Among the signals tested, LED devices consistently outperformed devices using flashtube or incandescent technology. This is due to the higher effective intensities presented by the LED devices as compared with incandescent and flashtube devices. Even though a flashtube has much higher *peak* intensity than does an LED, its flash is so short (17-60 microseconds in our tests) that its *effective* intensity is quite low. The test observers rated white and red signal colors with moderate to rapid flash rates and/or an irregular flash pattern higher than other signals. Through this testing, RDC also learned that response to signals was much better when the subjects viewed signals against a dark background (looking out to sea), rather than against one with varying background "clutter" associated with a populated area.

From the 2011 testing, RDC recommended further work to identify an optimal range of LED signal characteristics including: which colors are more effective or attention-getting, whether some flash rates are more effective than others, the effect of flash patterns (e.g., S-O-S[1] and other irregular patterns). The project focus was not to develop a new technology; rather, the focus was to determine the most conspicuous signal that existing technology needed to produce.

Throughout 2012, the RDC project team investigated what might be the "best" way to pose the following scenario in a research study: "Search and Rescue authorities advise a mariner of a distress in their general geographic area, and ask the mariner to be on the lookout for any type of signal that might indicate the location of the distress." As learned from device performance and subject response in the 2011 testing, the scenario would require a "nighttime, maritime background environment," so as to provide background clutter (other lights from shore or on the water), against which a mariner (or searcher) would need to identify a distress signal.

In mid 2012, RDC worked with the U. S. Navy Submarine Medical Research Laboratory to investigate an experimental approach to address this issue. This work included a literature review and development of a laboratory experiment. The literature review and background work pointed to a "compound-signal" (both color and pattern—much like this project's end result), but the potential duration of the effort was well in excess of the project sponsor's required completion date.

At this stage, the RDC team determined that the mix of available time and resources directed a focused approach. Specifically, at the outset of this portion of the project, the sponsors concurred that the project team would develop signal characteristics (intensity, chromaticity/color, and temporal pattern) to provide a signal discernible at night, at a range of 6 NM (searcher to signal), in 10 NM of meteorological visibility.

This phase of the project had a two-part strategy: use a laboratory (controlled) setting to determine a narrow subset of colors and flash characteristics, then use field testing (real world conditions) to validate the lab findings. Initially, the RDC team considered using a vessel-bridge simulator to provide a setting and

[1] Distress signal in Morse code

background lighting environment. However, since the project was evaluating narrow-spectrum LED signals rather than a broad-spectrum mix of red-green-blue light, the team ruled out this option. The project did consider other options, including working through other research institutions, but due primarily to schedule constraints, decided to develop a research framework in house, and contract for its completion, including both laboratory and field testing.

In October 2013, RDC began a concerted effort with Science Applications International Corporation (SAIC) and Leidos, Inc. to advance previous work, and analyze/establish the characteristics for LED devices to make them effective distress signals. This work would identify the specific ranges of flash rates/flash patterns, colors, and luminous intensity to ensure a visible, discriminable, conspicuous/attention-getting signal. Task elements include:

1) Literature Review. The project reviewed relevant papers on human visual sensitivity to identify characteristics (such as effective intensity, color, temporal frequency, flash pattern) needed in an effective distress signal. This included technical reports associated with visual, maritime aids to navigation, other transportation-related warning signals, and other visual, emergency or distress signals. The review allowed a cross-discipline review of previous work, with the potential of minimizing the scope of the signal characteristics that require testing.

2) Analysis of the Nighttime Maritime Visual Environment. This included determining the range of lighting a mariner might experience while searching for a signal, from dark, open water, to the lighting associated with complex background clutter from populated areas and lighted marine aids to navigation. As the project intended to use a laboratory setting for signal evaluation, the project needed the ability to quantify and recreate levels of "background clutter" as viewed by the laboratory subject.

3) Human Perceptual Laboratory Study. By using psychophysical methods to evaluate visual response to distress signal characteristics, the project gained an understanding of visual stimulus characteristics of common production LEDs that make a potential distress signal visible and conspicuous in the nighttime maritime visual environment. Under controlled conditions, experimenters had the ability to present a large number of stimuli (light signals) to test subjects, without having to account for the large number of variables that present themselves during a real-world field test in the maritime environment, particularly changes in weather and visibility.

4) Field Study: The culmination of the project determined what actually worked under real-world conditions. Once signal characteristics were narrowed down to those that are "better" than others, the project used actual operating environmental conditions to validate lab results, and included the opportunity to compare actual, off the shelf devices and pyrotechnic flares against the "designed" signals.

This report documents the procedures and results to determine the characteristics of a detectable, conspicuous, and discriminable distress signal.

NOTE: The information in this report is based solely on visual signal identification, with the study conducted for unaided human eye visual detection capabilities. Electronic-optical sensors, such as night vision imaging systems (NVIS) may require a characteristic that includes a signal in the sensor's optimal response range.

2 BACKGROUND

This section includes information concerning vision, conspicuity, signal terminology, current domestic maritime distress signal regulation, and laser signals. The information may help the reader better-understand the rest of the report.

2.1 Nighttime Vision

The human eye contains photoreceptors (light-sensitive cells) in the back of the eye (the retina) called "rods" and "cones" (due to their shapes when viewed under a microscope).

In daylight or under normal indoor lighting, a human uses daytime (or "photopic") vision, provided by the cones. Three types of cones – red, green, and blue –allow us to see in color. The cones are densely packed, especially in the very center of the retina (the "fovea"), which allows very acute spatial vision (i.e., humans can read very small print and see fine details).

At night, with little or no light, humans see using rod vision, or night ("scotopic") vision. Rods are about one thousand times more sensitive to light than are the cones. In dark environments, the rods "see" things that the cones cannot. Unlike human color vision in daytime, rod vision is black and white (shades of gray). Rods are also more sparsely distributed in the retina than are cones, meaning rod vision is not nearly as acute as cone vision. A person with normal, 20/20 daytime vision will generally see over ten-times worse (i.e., less than 20/200) in the dark or in very dim illumination. Thus, a human can't read the small print on nautical charts or computer displays with only the rods.

Rods and cones are sensitive to different wavelengths of light (called "spectral sensitivity"). The visible spectrum (the wavelengths of light that the eye can see) goes from ~400 nanometers (nm) to ~700 nm. The shorter wavelengths (~400-450 nm) appear violet or blue using daytime vision, and the longer wavelengths (~650-700 nm) appear red. Studies show that under normal daytime light levels (cone vision), the human eye is most sensitive to light near 555 nm (appears yellowish-green). Our nighttime (rod) vision is most sensitive to light around 505 nm, which would appear cyan (blue-green) to the cones. However, 505 nm light (and light of all wavelengths) appears gray to the rods (our nighttime receptors). This basic understanding about cone and rod vision serves in discussion of the attributes for light signal visibility.

2.2 Conspicuity

VDSD effectiveness depends on the ability of an observer to see and understand the light as a "signal." The VDSD must have characteristics that allow an observer to see it in the visual environment (e.g., at night, surrounded by the lights of a busy harbor). An effective VDSD must be large enough and intense enough so an observer (or searcher) can see it at a sufficient distance for positive identity and location. The spectral characteristics ("color") of the light are important, as daytime and nighttime vision are most sensitive to different parts of the visible spectrum. An effective VDSD must "stand out" (be distinguishable) from other light sources in the environment so that even a less-trained, tired, or less-attentive observer will "see" the light and respond appropriately. A unique flash pattern or frequency could both capture attention, and distinguish the signal from other, common flashing lights. All these qualities contribute to a signal's "conspicuity."

2.3 Flashing Signals and Intensities

Based on the project work that resulted in the 2012 report Suitability of Potential Alternatives to Pyrotechnic Distress Signals, the RDC project team determined that LED signals provided a degree of conspicuity far greater than existing xenon, gas-discharge tube devices (strobes or flashtubes). Even though a flashtube signal has a very high "peak" intensity, the duration of the flash is extremely short. As the report described, a signal's "effective intensity" provided a greater basis for signal detectability than a signal's "peak intensity."
Effective intensity is a measure of the visual effect of a flashing light. The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) uses the concept of effective intensity to quantify the impact of flash characteristics on the human visibility of signal lights. A flashing light with the same effective intensity as a steady-burning light will provide the same visual effect (i.e., for a human observer).

Effective intensity is calculated from the intensity of the flash and the duration of the flash (in seconds). Depending on the circuitry that generates a flash, each distinct flash could have a fixed intensity for the entire duration of the flash (Figure 1-top) or a "flash" could consist of a series of very-rapidly-repeating flashes or flicks (e.g., pulse width modulation) that collectively appear to the eye as one discernible flash (Figure 1-bottom). In the case of very-rapidly-repeating flashes, the average intensity of the modulated flash must be determined before the effective intensity can be calculated. In the case of a fixed-intensity flash, average intensity is equal to the fixed intensity.

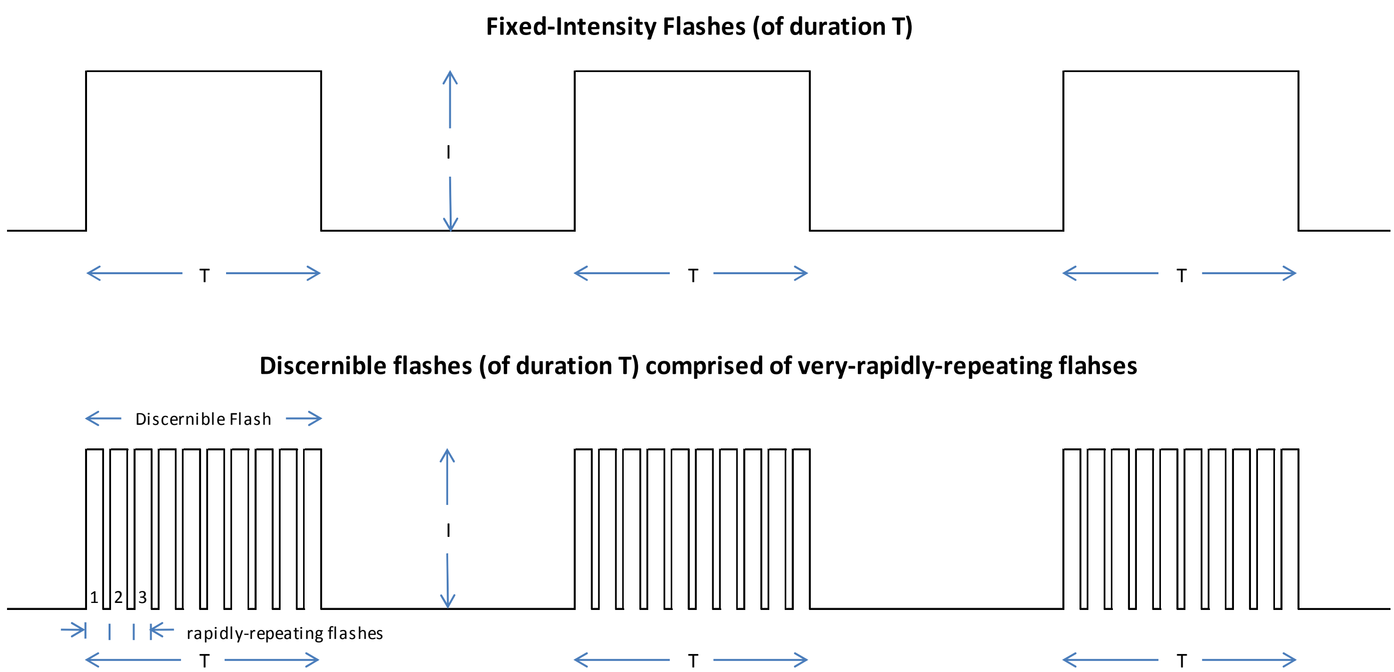

Figure 1. Example of signals with fixed intensity flashes (top) and very-rapidly repeating flashes comprising a discernible flash (bottom).

IALA (2008b) uses the "Talbot–Plateau law" to determine the average intensity of the discernible flash when it is made up of a series of very-rapidly-repeating flashes that exceed the "flicker fusion rate" (~15Hertz (Hz) under scotopic or low-light conditions to ~60Hz under photopic or well-lit conditions).

IALA applies the "Blondel-Rey equation" to calculate the effective intensity or "visual effect" of the flash using the average intensity and the flash duration.

(Note: IALA offers a full discussion on applying these two principles, including applicability beyond detection threshold. As the work in this report pertains to a marine distress location signal, the project bases its work on the IALA assumptions.)

To determine the average intensity of the discernible flash made up of very-rapidly-repeating flashes, IALA first applies the Talbot-Plateau law to determine the integrated intensity (J):

$$\mathrm{J} = \int_0^T I\, dt$$

where I is the time-dependent intensity of each rapidly-repeating flash, and T is the period of time of the discernible flash (Figure 1). Thus, the average intensity of the discernible flash is:

$$\mathrm{I}_{\mathrm{average}} = \mathrm{J} / \mathrm{T}$$

where T corresponds to the period of integration (i. e. the length of time of the discernible flash). If the waveforms of the very-rapidly repeating flashes comprising the discernible flash are rectangular, then the average intensity of the discernible flash can be simplified to:

$$\mathrm{I}_{\mathrm{average}} = \mathrm{I} \times \mathrm{d}$$

where d is a "duty-cycle" coefficient ranging from 0 to 1 (i.e., 0% to 100% duty cycle) for the very-rapidly repeating flashes.

Next, IALA recommends the Blondel-Rey equation to evaluate effective intensity. The equation is limited in its application to flashes of rectangular or quasi-rectangular form (for our purposes, flashes from non-rotating, LED sources):

$$\mathrm{I}_{\mathrm{e}} = \frac{I \times T}{a + T}$$

where I is either the intensity of the fixed flash or the average intensity of a rapidly-repeating flash (e.g., PWM flash) in candela, T is the duration of a single, discernible flash (in seconds) and a is a human visual system response time constant, per IALA, 0.2 sec for nighttime observation.

"Duty cycle" refers to the percentage of time that a signal is on (producing light). For the remainder of this report, duty cycle refers only to the discernible flash. Figure 2 provides examples of flashing signal patterns that depict duty cycle.

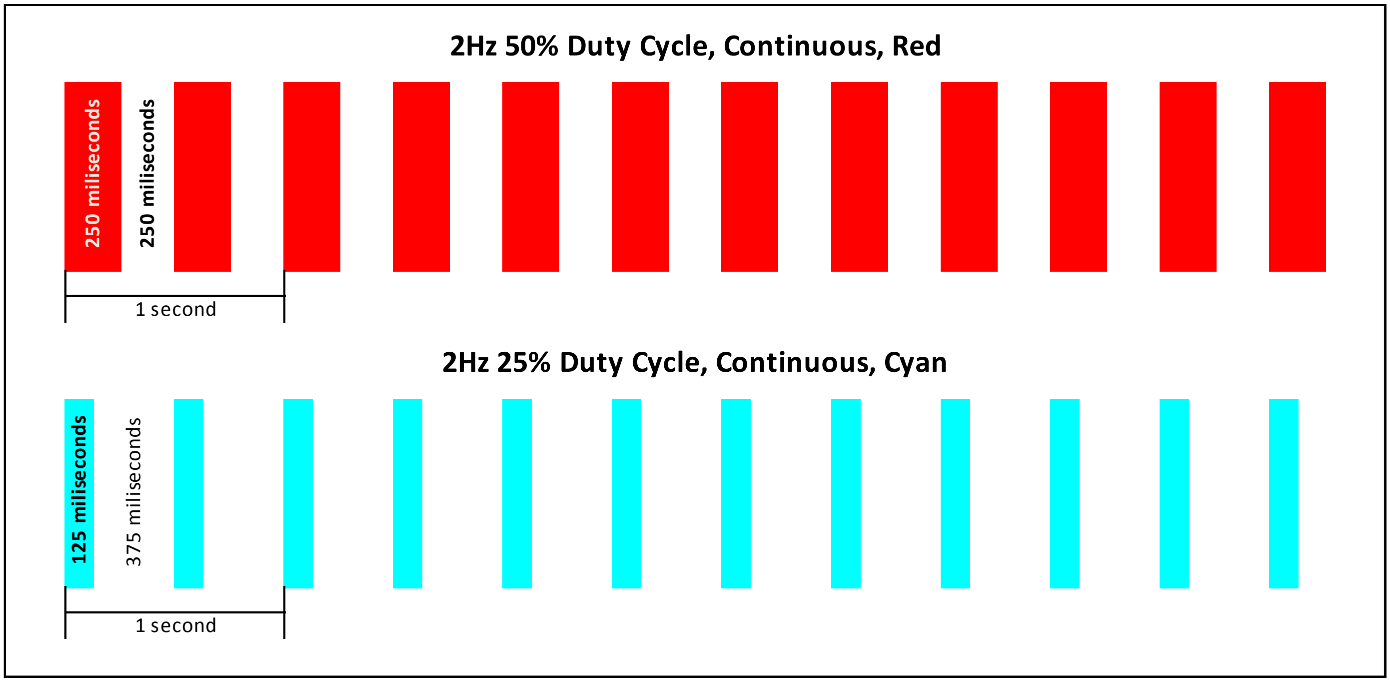

Figure 2. Flashing signal pattern examples.

The top diagram of Figure 2 depicts a 2Hz signal (2 flashes per second). With a 50% duty cycle, each flash will be 250 milliseconds (ms), with 250 ms "eclipse" (or off-time) between them. The Bottom diagram in Figure 2 shows the effect of a lower duty cycle. Though the signal is 2 Hz, with 2 flashes per second, the flash duration is only 125 ms with a 375 ms eclipse.

2.4 Existing Visual Distress Signal Requirements

2.4.1 Carriage Requirements

Table 1 provides the applicable regulatory requirements for carriage of visual distress signals aboard US vessels. Six allowed flare types meet day and night carriage requirements for recreational vessels, while the regulations allow only two signals that are not pyrotechnic in nature: a "distress flag" as defined in Title 46 Code of Federal Regulations (CFR), Section 160.072 for day, and an "electric S-O-S distress light" defined in 46 CFR 161.013 for night. In considering the project's technical scope (a focus on LEDs as alternatives to pyrotechnic distress signals), the project team decided to address only the requirements for a *nighttime* signal. Also, to further limit scope, the project emphasized distress signal carriage requirements for recreational vessels.

The project team considered the 500 candela (cd) red hand flare and the electric distress light for boats as "reference" signals.

Table 1. Visual distress signal requirements for U. S. vessels[2].

Distress Signal	Recreational Boats - Day	Recreational Boats - Night	Commercial Fishing Vessels	Sailing School Vessels	Small Passenger Vessels	Other Commercial Vessels
Red Hand Flare - 500 candela (160.021)	X	X	X Within 50 miles of coastline	X	X	X Great Lakes Only
SOLAS Red Hand Flare -15,000 candela (160.121)	X	X	X	X	X	X Great Lakes Only
Red Parachute Flare -20,000 candela (160.036)	X	X	X Within 50 miles of coastline	X	X	
"SOLAS" Red Parachute Flare - 30,000 candela (160.136)	X	X	X	X	X	X
Red Meteor Flare - 10,000 candela (160.066)	X	X	X Within 3 miles of coastline			
Combination Flare and Smoke Signal (160.023)	X	X	X Within 3 miles of coastline			
Hand Orange Smoke Signal - 50 seconds (160.037)	X		X Day Only Within 50 miles of coastline	X	X	X Great Lakes cargo vessels less than 150 gross tons
Floating Orange Smoke Signal - 5 minute (160.022)	X		X Day Only Within 50 miles of coastline		X	
"SOLAS" Floating Orange Smoke Signal - 3 minute (160.122)	X		X			
"SOLAS" Self-Activating Floating Orange Smoke Signal - 15 minute (160.157)	X		X Day Only Within 3 miles of coastline			Used as ring lifebuoy marker, one on each side of the vessel, international voyages
Distress Flag (160.072)	X		X Day Only Within 3 miles of coastline			
Electric S-O-S Distress Light (161.013)		X	X Night Only Within 3 miles of coastline			

Note: Section number from 46 CFR indicated in parentheses after distress signal name

X indicates that the signal is generally acceptable for the indicated use. Limited uses for certain signals are described in the boxes

[2] From USCG Lifesaving and Fire Safety Division website: www.uscg.mil/hq/cg5/cg5214/vds.asp#vdsrequirements

Summarizing 46 CFR 161.013 (Appendix A), which established standards for electric distress lights for boats, in 1979, the light must:

Emit a white light which, (a) if over an arc of the horizon of 360 degrees, have a peak Equivalent Fixed Intensity (EFI) of at least 75 cd in a horizontal plane; or, (b) if a directional beam of light, have a minimum peak EFI of 2,500 cd.

and

Have a flash characteristic of the International Morse Code for S-O-S: short flash of 1⁄3 second (sec) duration, long flash of 1 sec duration; 1/3 sec dark period between each short flash, 1⁄3 sec dark period between each long flash; 2 sec dark period between each letter, and 3 sec dark period between each S-O-S.

Except for the "irregular" S-O-S pattern, this characteristic does not align well with the "moderate to rapid flash rates" found favorable in the 2011 study. In fact, the 2 second dark period between letters and the 3 second dark period between S-O-S leaves far too much time without a signal.

2.4.2 Navigation Rules Sound and Light Signals

By Treaty and statute (Congress adopted them as the International Navigational Rules Act of 1977), the US follows the International Rules for Prevention of Collision at Sea (COLREGS). Both the COLREGS and 33 CFR, subchapter E, Inland Navigation Rules, recognize specific distress signals and their use in 33 CFR 83.37 which states, "When a vessel is in distress and requires assistance she shall use or exhibit the signals described in Annex IV to these Rules (33CFR part 87)."

Figure 3 illustrates the signals mentioned in Annex IV. The COLREGS include the signals on the left side of Figure 3 as distress signals, while 33CFR 87.01 (p) authorizes the "high intensity flashing light" on the right side of Figure 3.

Both the COLREGS and the Inland Navigation Rules include Rule 36, Signals to attract attention: "If necessary to attract the attention of another vessel, any vessel may make light or sound signals that cannot be mistaken for any signal authorized elsewhere in these Rules, or may direct the beam of her searchlight in the direction of the danger, in such a way as not to embarrass any vessel."

From the foregoing, any "new" distress signal , besides approval under the carriage requirements of 46 CFR, must also meet the requirements of the COLREGS and 33 CFR, particularly, a signal that "cannot be mistaken for any signal authorized elsewhere."

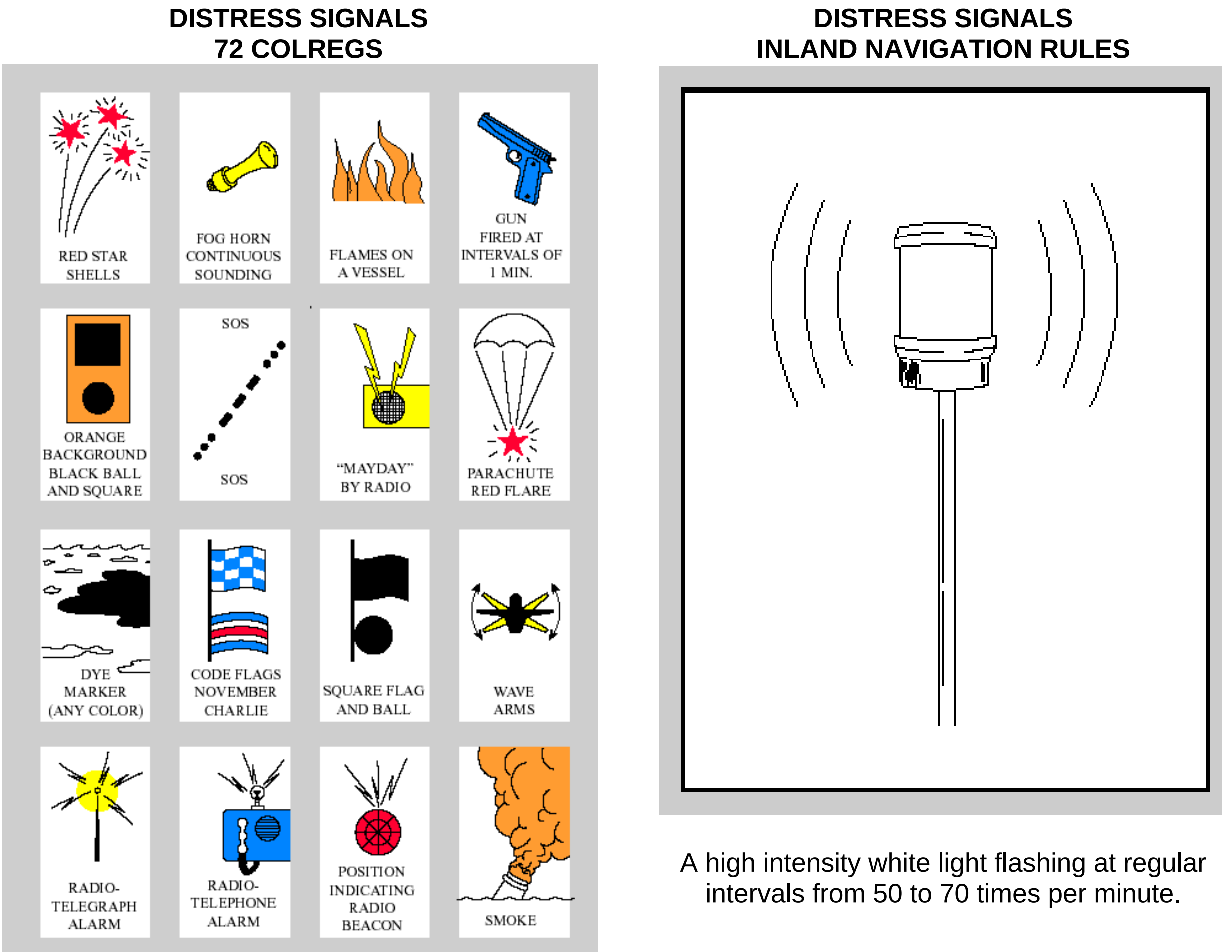

Figure 3. Distress signals required by COLREGS and Inland Navigation Rules, Rule 37[3].

2.5 Laser Devices as VDSDs

Throughout this project, interested parties have expressed concern that the work here does not include evaluation of laser signal devices.

Upon initial deliberation, a laser would seem like an obvious choice for a visual signaling device given its high intensity. Trials have shown that the output power of a laser allows observers to see it at distances of greater than 20 miles. As an example, two similar devices, as marketed, have the following specifications:

Table 2. Examples of laser device specifications.

Wavelength	532nm (Green)	650nm (Red)
Beam Shape	3 deg. divergent laser line	Collimated 5 deg. (1 mrad.) divergent laser line
Nominal Ocular Hazard Distance	1mW output at 9', beam width 0.78"	1mW output at 27", beam width 0.08"

Note: Table from vendor information sheet. Deg: degree (of arc); Mrad: milliradian; mW: milliwatt

[3] From U. S. Department of Transportation, United States Coast Guard, Navigation Rules International-Inland

This device, when held correctly as marketed, is intended to project a vertical line of light. For the above examples, the 3-degree line (beam height) is approximately 3,100 ft at 10 NM, and the 5-degree line is approximately 5,200 ft at 10 NM. A 1-milliradian line-width gives a beam width of approximately 60 ft at 10 NM.

In 2002 the RDC conducted an informal, field observation trial of a "Rescue Laser Flare." (This device is thought to be similar to the "red" example in Table 2.) Researchers conducted the trial with a signal operator/observer at a fixed observation platform on the shoreline of Avery Point, Groton, CT and one observer/operator onboard a large commercial ferry traveling between New London, CT and Orient Point, NY. The two observers were at approximately 10 and 20 feet above water level (AWL), respectively. The observers could see the signal at a long distance (in this case 8-10 NM). However, both observers (both on shore and on the ferry) noted that the signal appeared as a very brief flash of light. Both participants noted that it was difficult to know *exactly* where to train the device, even with ferry lights and shore landmarks as "pointers." Due to the motion of the ferry created by the seaway, the operator on the ferry noted that it was not possible to keep the device pointed in the desired direction.

From a surface-to-surface orientation, the shore observer confused the device signal with red AtoN sources. At approximately 7 miles, the flare appeared similar to a red buoy lantern that was much closer.

This type of device, though having a very powerful signal, produces a highly directional, very fine, very brief (to the observer), *point source* of intense light (the observer does not see the vertical line). The directional nature of the source translates into an observer quickly losing the source when the observer in not in the exact line of signal. Aiming and sweeping techniques are critically important to the success of the signal. For effective use, the distressed individual must be able to *accurately* direct the beam, in a sweeping motion, in the direction of the searcher.

Initially, the project did not want to rule out this type of device, but in the early project stages, the project team decided to limit effort to a signal that manufacturers could easily and effectively adapt to a device that displays a signal of uniform intensity, in a hemispheric pattern. This hemispheric pattern allows signal visibility, regardless of the searcher's approach direction, and does not rely on the distressed individual to try to determine that location.

3 LITERATURE REVIEW

The literature review had two purposes: (1) review other relevant work on human visual sensitivity to identify characteristics needed in an effective distress signal, and (2) take a cross-discipline approach to determine if work associated with other transportation–related signals or other emergency signals was applicable to this project, potentially minimizing this project's scope of effort. As the project team was familiar with LED advances, particularly in marine aids to navigation, and since the project goal was to provide a characteristic for a conspicuous marine signal, logic indicated that previous work to improve marine aids to navigation (AtoN) signals could direct this project's course. Reiterating, "signal characteristic" includes color (chromaticity), flash pattern and frequency, and intensity.

In terms of flash rate, Laxar & Benoit (1993) looked at response times for detecting small (2 minutes of arc) lights flashing at either 1 Hz, 2 Hz, or 3.85 Hz to simulate an AtoN at a distance. They found that the 3.85 Hz flash rate produced the fastest response times, followed closely by the 2 Hz flash rate. The slower 1 Hz flash rate not only produced much slower response times, but also produced twice the errors as either of the

other two flash rates. Kelly (1974), using a much larger stimulus size, examined the sensitivity to flickering red, green, blue, and achromatic (white) lights. For red, green, and achromatic lights, the peak sensitivity was to flash rates near 8 Hz. But for blue lights, the peak sensitivity was in the range of 1-4 Hz. These two studies suggest that a good flash rate for a distress signal would be in the range of 2-4 Hz, possibly higher for red and green signals. However, it's not clear what impact, if any, the stimulus size might have had on these results (particularly on Kelly's results).

For color (dominant wavelength), the problem is more complex. Since the signal needs to be seen at night, the rod (scotopic) system will be the primary determinant of detection of the signal, since the rod system is so much more sensitive than the cone (photopic) system. Once the light is intense enough to activate the cones, the signal may be detected by both rods and cones, but the color of the light signal will be identified via the cone system. In a visual search, the target is often detected in the peripheral field, stimulating eye movement to focus on the target. The peripheral detection will be mediated by the rods. This indicates a component of the visual signal having its dominant wavelength near the peak of the scotopic spectral sensitivity curve, 505 nm (cyan or blue-green).

Smith (1940) conducted a study evaluating the relative effectiveness of various colors under low light (about 0.25 foot candle) conditions. Quoting Smith, "When the colors included in the foregoing experiments are seen in very dim light without contrast effect, orange is the most effective color. Its advantage is greatest when compared with blue, next with red, then green, and least yellow. Red is superior to blue, but inferior to the other four colors. Yellow is more effective than blue, red, and green in the order here indicated, while green is more effective than blue, but ranks below the other four. Blue shows the least visibility of all."(Smith, 1940)

Kelly (1974) states, "Throughout most of the spatio-temporal domain, the green sensitivity is greater than the achromatic sensitivity, the red is less, and the blue is least of all."(Kelly, 1974).

Rea (unpublished) goes on to say a short-wavelength color (i.e., green) may be most effective for peripheral visual detection (Weale 1953) and detection under mesopic conditions to minimize energy requirements. An additional approach for visual distress signals could be to use alternating color and intensity simultaneously to provide a distinct spectral and temporal pattern (Rea, et al., 2009).

The conspicuity of an object in the environment is a property of both the object (color, size, brightness, flash rate, etc.) as well as the background/environment in which the object is embedded, i.e., how well it stands out from its environment. Wagner & Laxar (1996) showed that signals with different characteristics than the background were easier/faster to detect. For example, light targets with an alternating pattern at a diagonal orientation (tilted at 45^{O}) were detected more quickly against a background of horizontal and vertical light patterns. Hence, conspicuity describes a relationship: the degree to which the object is visually similar to its surrounding scene (Wertheim, 2010). Therefore, a conspicuous stimulus will have features that differ from those in the background.

Rea et al. (2009) indicated that a minimum scotopic luminous intensity of 20 cd appears necessary for nighttime detection of a flashing light signal array, but since a visual distress signal is a single source of light rather than an array at 5 miles, a higher intensity of a single light may be necessary to ensure reliable detection. Higher intensities might be necessary for reliable detection in visually complex environments with many irrelevant lights present.

Selection of a color for a maritime distress signal would also be based on the colored lights that are present in a nighttime maritime environment. Conspicuity of a signal is not just a function of the signal intensity, flash pattern, and color alone. The degree, to which the selected distress signal differs from other light (in terms of color and flash rate) in the environment, will have an impact on the signal's conspicuity.

4 ANALYSIS OF THE NIGHTTIME MARITIME ENVIRONMENT

As used in this context, the nighttime maritime environment refers to the amount of lighting (or sources of "luminance") a mariner encounters, on a dark night, when looking towards the horizon. At sea, with no other vessels near, the mariner may encounter no lighting sources, but as the mariner nears shore, they might see navigation lights from other vessel traffic and vessels at anchor, aids to navigation, and multiple sources of lighting on shore (e.g., buildings, bridges, street and highway lighting, athletic venues, etc.).

In the 2011 RDC study, observers were able to detect and identify many of the LED signals at 5 NM, when viewing them against a dark background, looking seaward with only occasional passing vessels. On the other hand, these same observers had a much more difficult time detecting those same signals at 2.5 NM, when viewing them against the lights of Newport, RI in the background.

As noted earlier in Section 2.2 (Conspicuity), for a searcher to identify a distress signal, the signal must have characteristics that make it different or discernible from the lighting "clutter" the searcher views the signal against. Initially, while determining appropriate locations for field testing in early-November 2013, the project team found noticeable differences in the concentrations of shore lights when looking across Lower New York Bay from Sandy Hook, NJ (Figures 4 thru 7). The project team subjectively decided to consider four distinct levels of shore lighting clutter: negligible (almost no background lighting), sparse, moderate, and substantial (high-density and intensity of shore lights).

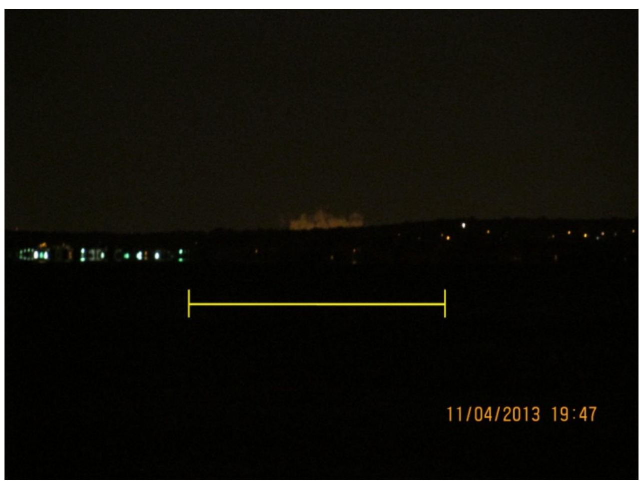

Figure 4. Example of "negligible" background clutter (indicated by yellow line).

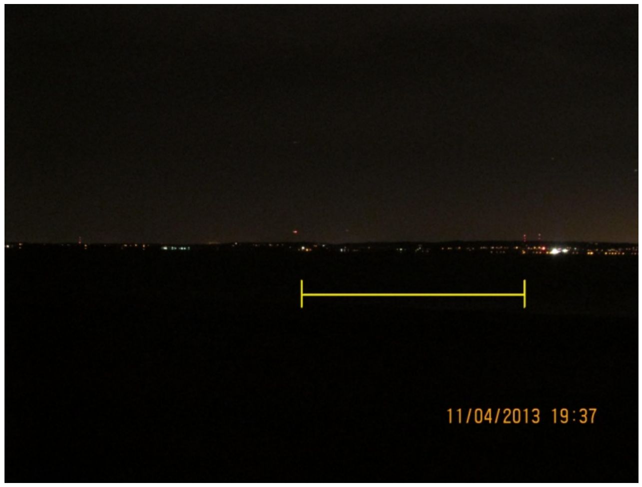

Figure 5. Example of "sparse" background clutter (indicated by yellow line).

Figure 6. Examples of "moderate" background clutter (indicated by yellow lines and pertains only to the horizon-level lights under the bridge).

Figure 7. Example of "substantial" background clutter (indicated by yellow line).

As noted in Section 3 (Literature Review), previous researchers studied the effect of different signal characteristics on observers, as relates to potential improvements in maritime AtoN. Coupled with the scientific research, IALA has provided numerous recommendations for the performance of maritime navigation signals. Since this project's goal is to develop a conspicuous maritime visual distress signal, the project team's efforts used the IALA recommendations as a basis.

IALA defines the distance at which an observer can see maritime signal lights in Recommendation E-200-2 (IALA, 2008a) "On Marine Signal Lights" Part 2 - Calculation, Definition and Notation of Luminous Range:"

- The nighttime *nominal range* of a maritime signal light is the distance in nautical miles at which this light produces an illuminance at the eye of the observer of 2×10^{-7} lux (lx).
- In the case of a light that appears as a point source, the *luminous range* is defined as the maximum distance at which a light can be seen (both color and flash pattern discernible), as determined by the luminous intensity of the light, the meteorological visibility, and the required illuminance of 2×10^{-7} lx at the eye.

Based on mariner input, the CG Ocean Engineering division was aware that "background clutter" has the effect of diminishing the luminous range of lights, i.e., other lights on the water and/or on shore make it harder for the mariner to find a specific lighted aid to navigation. In an attempt to specify a more realistic luminous range of AtoN lights in the presence of background clutter, the Coast Guard looked at a wide-ranging sample of CG AtoN lights in the maritime environment against scenes comprising various degrees of clutter. These observations revealed that the luminous range of a light is hugely dependent on the 1, 2, or 3 extraneous light sources that are immediately behind/adjacent to the actual AtoN.

For the most part, background clutter did not receive more attention because it was hard – perhaps impossibly hard – to quantify, and therefore technical authorities have always tested the luminous range of AtoN lights against a totally dark background because that was doable. The Coast Guard, in an attempt to at least acknowledge that background lighting has a huge impact on luminous range, conducted informal observations of AtoN against "minor and substantial" (purely subjective levels) background scenes. The outcome of these observations showed that the illuminance required at the eye of an observer needs to be increased by a factor of 10x for minor, and by a factor of 100x for substantial, background lighting clutter.

The project team decided that background clutter needed to be clearly defined – if not accurately quantified – so that levels of background clutter seen in the nighttime maritime environment could be replicated for laboratory testing (i.e., present equivalent levels of luminance and degree of background clutter to the subjects of a lab study), and used as reference in real-world field experiments and demonstrations.

In mid-November 2013, a project field team collected data to quantify, categorize, and document the four, originally-subjective background lighting conditions: negligible, sparse, moderate, and substantial.

The team set up instrumentation at the north end of the beach at Sandy Hook, NJ (Figure 8). This location offered unobstructed views across Lower New York Bay with low-light backgrounds to the Northwest (Staten Island) and high-light backgrounds to the North (Coney Island).

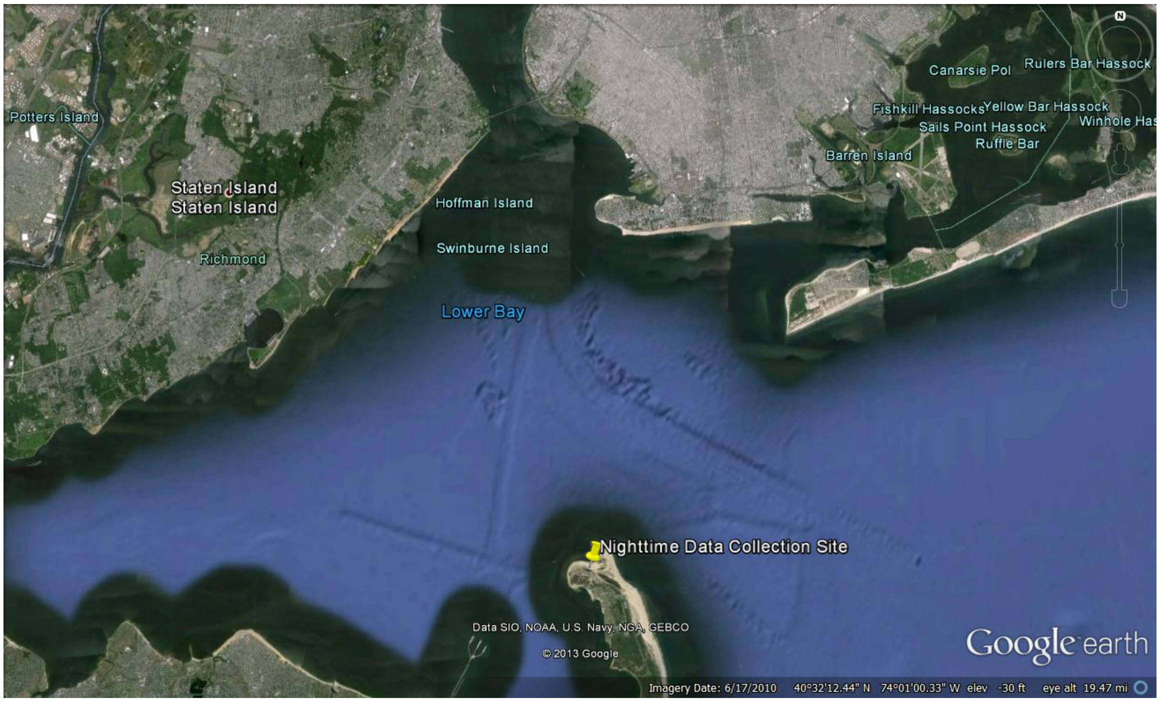

Figure 8. Nighttime maritime environment data collection site.

Team members collected images of 11 scenes using a Radiant Imaging Colorimeter. These images capture overall scene luminance (Figure 9 is an example of a colorimeter image) and chromaticity (color of lights) distribution. Additionally, a high-definition video camera recorded the temporal characteristics of flashing lights. (The test developers would apply these three measurements to replicate the actual background scene in the laboratory.)

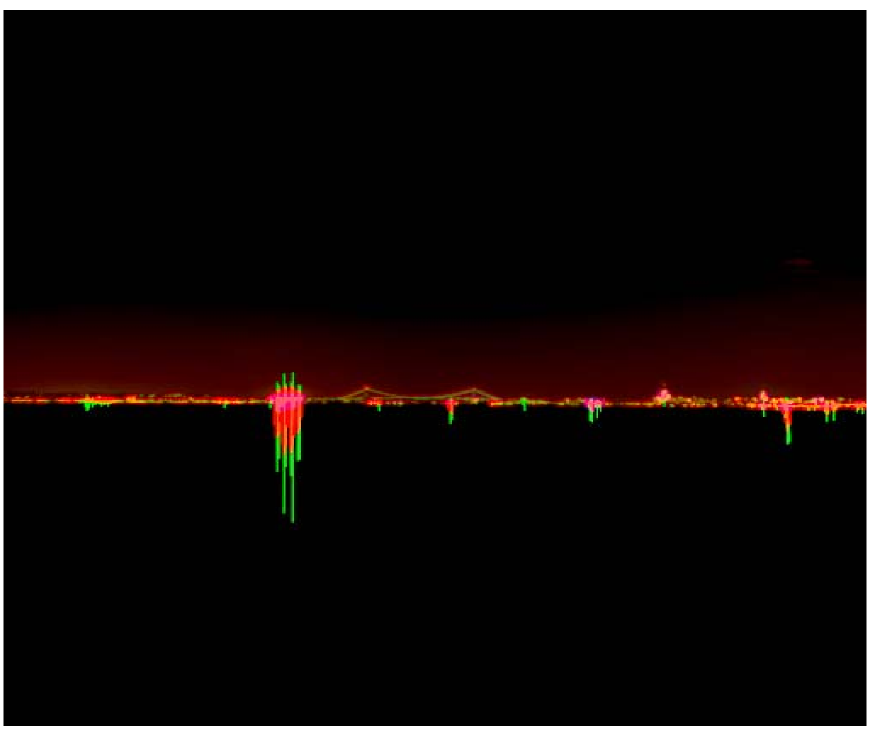

Figure 9. Example of image capture from radiant imaging colorimeter.

Lab test developers later extracted luminance and chromaticity distribution from the images to quantify these aspects of each scene. Table 3 lists the minimum, maximum, and mean luminance levels and bearing from Sandy Hook (see Figure 8) of the captured scenes.

Table 3. Scene luminance levels.

				Luminance (cd/m2)		
	FileName	Time (Zulu)	Bearing (M)	min	max	mean
Data Set 1	Img1	2204	30	0.1095	11.1113	0.664
	Img2	2207	45	0.0836	10.6558	0.5132
	Img3	2212	0	0.0005	8.8341	0.3941
Data Set 2	Img4	2213	330	0.0648	7.75303	1.1398
	Img5	2215	0	0.0178	14.4055	0.2774
	Img6	2217	30	0.0176	14.7754	0.2235
	Img7	2221	60	0.0081	3.3554	0.0871
Data Set 3	Img8	2259	60	0.0017	1.3684	0.0445
	Img9	2302	30	0.0004	1.5105	0.1403
	Img10	2305	0	0.003	1.4141	0.0409
	Img11	2307	330	0.0019	1.4455	0.0299

In conjunction with the subjective scenes in Figures 4 through 7, the test team used the quantitative luminance levels from the 11 images to determine representative values for the four background clutter categories. Later, they would deconstruct and resplice sections of the images so as to provide a consistent background clutter level across the entire laboratory screen.

5 LABORATORY TESTING

5.1 Overview

The foregoing sections show that a good distress signal needs to use color and flash rate/pattern to stand out from the background clutter. As Section 3 states, most of the basic research into the color vision mechanisms (e.g., Kelly, 1974) used relatively large stimuli. A searcher will see a distress signal at 6 NM, as a point source. Since color perception and temporal frequency sensitivity vary with field (signal or stimulus) size, the project did not assume that earlier findings with large fields (signals) would generalize to point sources. The project needed to look at the detectability and relative conspicuity of different colors and flash rates in the lab. As the AtoN studies showed, an easily detectable signal in the absence of visual clutter (background lighting) might be much more difficult to detect when the level of visual clutter is high. Other vision research indicates the same: visual clutter can cause decreased recognition performance and greater difficulty in performing a visual search task (Bravo & Farid, 2008). Therefore, the project used a laboratory environment to study how the addition of cluttered backgrounds affects recognition of point-source signals of different colors and flash rates.

Laboratory testing required by this project required the use of human subjects in the research. Test protocols were reviewed by the RDC Institutional Review Board (IRB) and were approved in compliance with COMDTINST M6500.1.

5.2 Laboratory Setup

The project performed laboratory testing at the Leidos, Inc. facility in San Diego, CA. Figure 10 depicts the general lab layout. The lab was 17 ft. wide and 42 ft. long. A screen for the display of background images was located at the far end of the room (right side of Figure 10). A ceiling-mounted projector, approximately 24 feet from the screen, displayed the background (clutter) images. Test subjects (observers) sat about 20 ft. from the screen. The lab walls were flat black, and any other reflective surfaces were covered in black felt to eliminate light reflections from the screen. The measured illuminance without a projected image on the screen was 3.73×10^{-3} lx, within the normal nighttime level of ambient illumination.

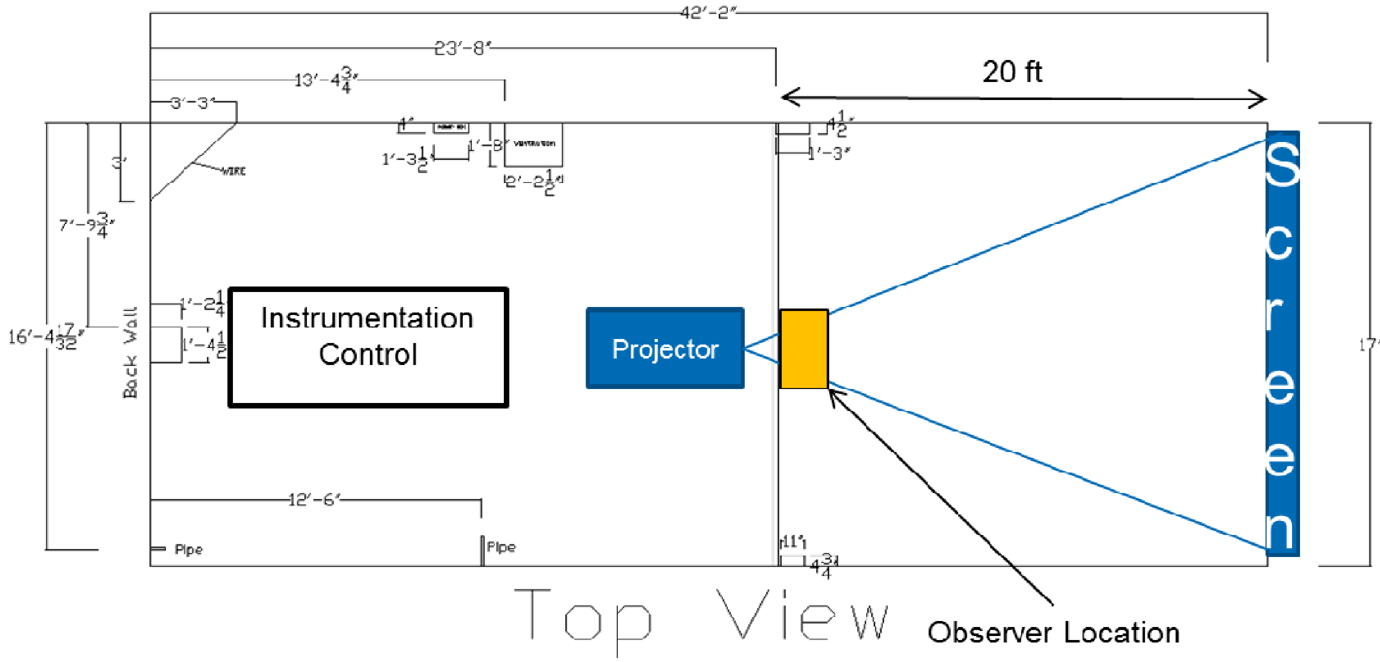

Figure 10. Laboratory setup.

5.2.1 Projector Specifications

The scene projector was a Panasonic PT-AE80000U home cinema projector, chosen for its brightness range (up to 2400 lumens (lm)), contrast ratio (500,000:1), and pixel density (1920x1080 pixels), enabling a precise replication of background clutter images.

5.2.2 Projection Screen

Leidos engineers designed and built the screen specifically for this experiment. The object was to replicate nighttime maritime scenes with a distress signal at or near the horizon, with a panoramic view of the background lighting. This required a wide screen. The lab team stretched commercially-available home-

theater screen fabric across a 16-ft. wide frame. The reflective portion of the screen was 2 ft. in height, with black felt above and beneath the screen to minimize reflections.

5.2.3 Background Images

Leidos used still images from the analysis of the nighttime maritime environment (Section 4) to create the backgrounds projected onto the screen. They took vertical sections from the images that reflected the four levels of background lighting density and intensity described in Section 4, and re-spliced composite background images to produce the same colors and intensities as measured in the field, equally distributed across the entire screen. The staff also coded dynamic features of the real-world environment, such as flashing buoys and flashing bridge lights, into the background scenes.

Given that earlier testing (Young, et al., 2012) had shown that virtually any light is detectable against a negligible background, the project excluded the negligible background condition from the lab tests. To preclude test subjects from memorizing where on the background scene test signals might appear, Leidos created five images for each of the three remaining clutter levels, allowing for random switching between the images at a given clutter level.

5.2.4 Test Signals

The lab test goal was to test the efficacy of using different color LED signals. Because LEDs have such narrow bandwidths, RDC ruled out producing the test signals with the Panasonic projector for two reasons: (1) there are nonlinearities in the processing of hue information such that a narrow-band light and a broad-band, RGB mixture will look different, even when they have the same dominant wavelength or same CIE values (Bieske, Csuti, and Schanda, 2006; Mizokami, Werner, Crognale, and Webster, 2006); (2) under nighttime ambient illumination conditions, the sensitivities of the three cone systems will vary, leading to a change in the color perception of the broad-band signal relative to the narrow-band one. Therefore, RDC required use of actual LEDs to produce the lab test distress signals.

Leidos staff constructed LED signal projectors with the capability to test seven, common LED colors (Table 4 and Figure 11). Each LED projector used an off-the-shelf LED and lens cluster which could focus the light from any of the seven LEDs directly ahead of the cluster (Figure 12). The light then exited the screen through a 0.2mm diameter aperture to produce a stimulus size of 6.8 seconds of arc at 20 feet (any stimulus with a diameter of ≤10 second of arc is considered to be a point source (Riggs, 1965)).

Table 4. LED colors used for laboratory testing.

LED Color	Dominant Wavelength or Color Temperature
White	4000o K
Deep Red	655 nm
Red	627 nm
Amber	590 nm
Green	530 nm
Cyan	505 nm
Blue	470 nm

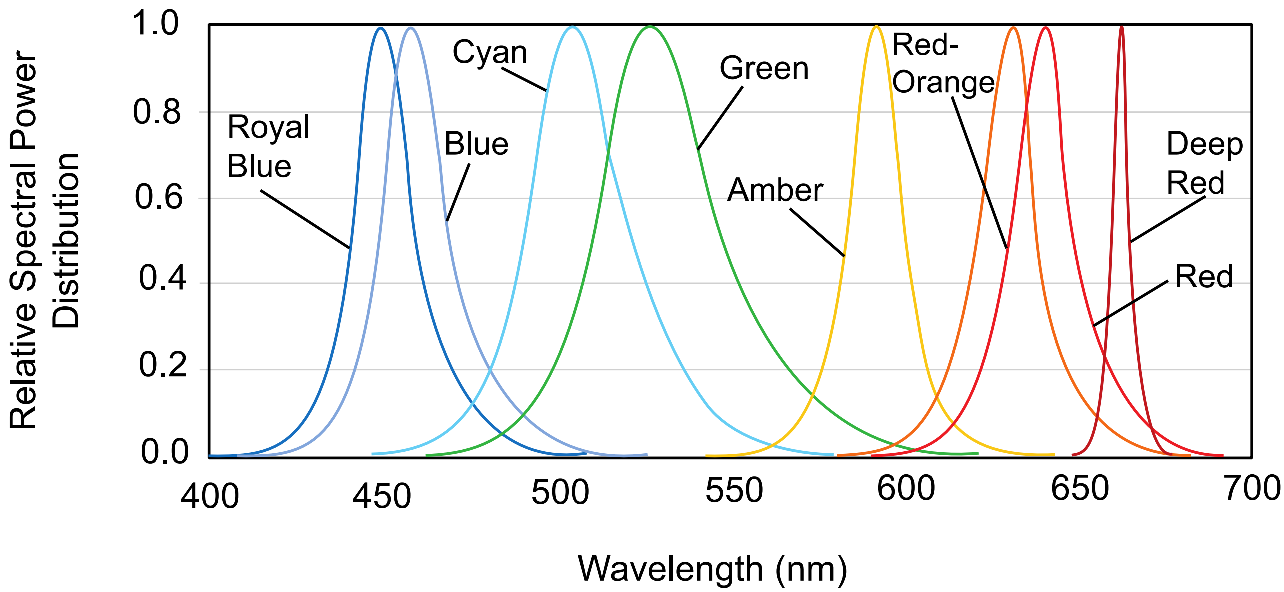

Figure 11. Spectral distribution of common LEDs[4].

Though there are two additional LED colors on the market, red-orange (617 nm) and royal blue (447 nm), the project did not consider them in lab testing. Royal blue has a very short wavelength, not easily detected by either the photopic (cone/daytime) or scotopic (rod/nighttime) systems. Since the red-orange LED dominant wavelength is so close to the red LED, the project team considered that the red and red-orange would have had similar detection rates.

Figure 12. Seven-color LED cluster for lab signals.

[4] White LED not shown

The formal laboratory test used a visual search paradigm: on a given trial, the experiment apparatus would display one signal, and the subject's task was to scan/search the background image until they found the test signal. In order to keep the search task as realistic as possible, the background had seven horizontal sectors (from left to right), with LED signal projectors placed in eight positions (Figure 13). Once the subject found the signal, he/she needed to indicate in which sector (1-7) the signal was located.

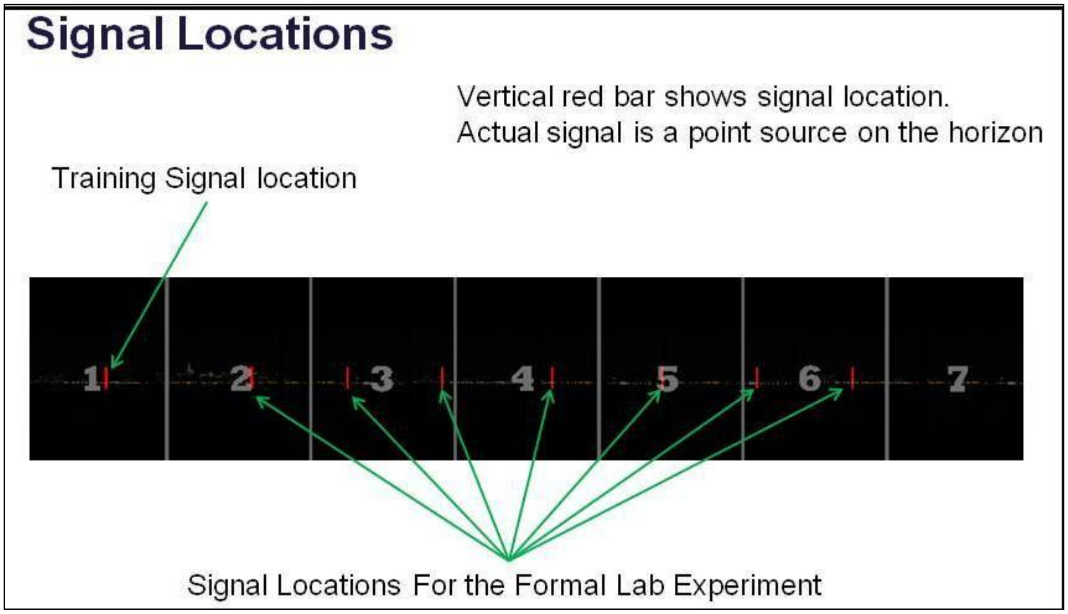

Figure 13. Laboratory signal locations against background clutter.

5.3 Pilot Tests

Because of the large number of variables (seven colors, multiple flash rates, three levels of clutter, seven signal locations), a single lab test would have been prohibitively long. As is common in perceptual experimentation, the project used a series of smaller pilot tests to winnow down the variables to a reasonable number for formal testing. Subjects for the pilot testing included both project-team members and Leidos employees not associated with the project.

5.3.1 Flash Frequency

Since signal brightness is likely to be the limiting factor for producing hand-held, battery-operated, electronic distress signals, many of the pilot studies sought to determine which colors and which flash frequencies would provide good conspicuity against maritime backgrounds at a lower luminance level. Testing found that for almost all LED colors, subjects identified a signal with a 4 Hz flash rate at a lower luminance value than a 7 Hz signal. This was especially true with substantial background clutter. Pilot test subjects mentioned that the 7 Hz signal looked more like a "shimmer" than a flash, making it harder to find. When comparing 4 Hz to 2 Hz signals, there was little to no difference between their identification thresholds. Maritime aids to navigation have slow flash rates (0.167 Hz – 1.0 Hz; US Coast Guard, 1990). In order to ensure the distress signal flash rate would not be confused with a navigation aid, the project team chose 4 Hz as the primary signal frequency for further testing.

5.3.2 Color

Because seven colors with multiple patterns and combinations would be too many test signals for the formal lab test period, the test team planned to reduce the number of LED colors to three "representative" colors: one long-wavelength color (red or deep red), one middle-wavelength color (amber or white), and one short-wavelength color (green, cyan, or blue).

The test team chose red over deep red because it yielded lower thresholds (i.e., could be easily seen at lower luminance/intensity levels).

Experimenters chose white over amber for two reasons: the spectral emission of the amber LED is close to that of sodium-arc lamps used in street lights on shore (making amber more readily confused with background light--corroborated by a paired comparison test of white and amber on both sparse and substantial backgrounds); and the white LED is more efficient (can get a higher light output with less wattage) than the amber LED.

The choice for the short-wavelength LED was difficult. The green LED had highest detection thresholds of the three, particularly against substantial background lighting. Also, AtoN studies found cyan to be a better choice than green for people with abnormal color vision. Blue tended to have slightly lower thresholds than did cyan. The project team chose cyan over blue due to potential, real-world transmissivity issues. Figure 14 is a MODTRAN4 (Berk, et al., 1999) generated transmission profile for the marine environment. In lighter winds, at 6 NM, blue (~470 nm) shows an approximate 15% reduction of transmissivity compared to cyan (~505 nm). Also, the 505 nm dominant wavelength of cyan is at the peak of the scotopic spectral sensitivity curve, meaning that cyan will be more detectable than either green or blue at very low light levels.

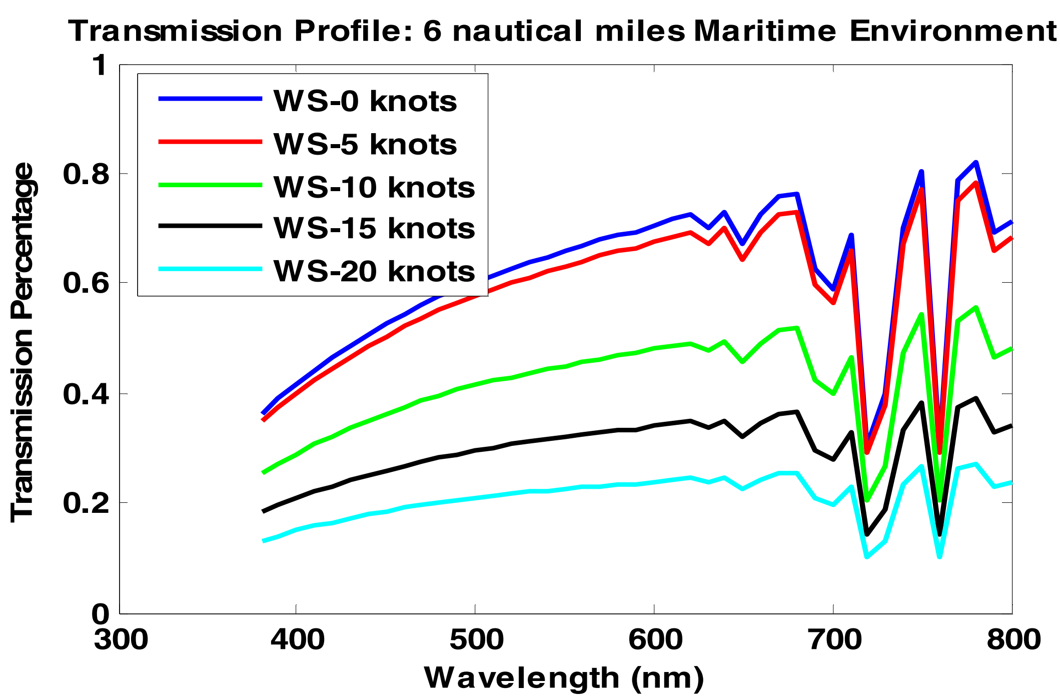

Figure 14. MODTRAN4 transmission profile, 6 NM, various wind speeds (WS).

5.3.3 Intensity

To compare signals of different colors in the lab, the experimenters tried to make them appear equally bright. Signal intensity is a powerful driver of conspicuity. If a person were to compare a dim cyan signal with a bright green signal, the green would be more conspicuous – *not* because of its color, but because of its greater intensity. Thus, in order to make judgments based solely on color, the subject must perceive the lights' intensities to be equal. The test team used a brightness-matching paradigm to find intensity levels of the white, cyan, and red LEDs that *appeared* equally bright. Extrapolating from the lab brightness levels needed to make the LED signals conspicuous against substantial background lighting in the lab, the experimenters concluded that for real-world conditions, the actual signal intensities would not be practical. Thus, experimenters limited the lab testing to only sparse and moderate background lighting conditions. Based on the brightness matching, the test staff chose signal intensity levels that were conspicuous against both these backgrounds.

The project team selected the following luminance levels (intensities) for the formal lab study: Cyan, 0.0666 cd/m^2; White, 0.09166 cd/m^2; and Red, 0.0824 cd/m^2.

5.3.4 Flash Patterns

One way to improve the conspicuity of a signal is to ensure its flash pattern is unlike anything else in the nighttime maritime environment. The project team used informal mock-ups to create different signal patterns.

Given the good conspicuity already noted for a regular 4 Hz signal, the test team retained that signal for further evaluation. The team also added a variant of the 4 Hz signal with a slight pause ("interrupt") after the first group of four flashes, and another slight pause after the next group of three flashes.

Since the 2011 RDC work found that an S-O-S signal (an irregular pattern of flashes) led to better conspicuity than a regular 1 Hz pattern, experimenters included an S-O-S as one signal pattern. As discussed in Section 2, the 46 CFR 161 S-O-S is a rather slowly-flashing signal, with significant "off-time." Given that human sensitivity to such low temporal frequencies is not good, the project team also developed two, faster-flashing S-O-S variants.

The team also developed a third pattern, a "chirp," in which the flash frequency changes from low to high (chirp up) or vice versa (chirp down). The changing flash rate would be different than anything else in the background and the team thought it would be conspicuous.

This process resulted in seven different flash patterns: two 4 Hz-based patterns, three variants of the S-O-S, and two chirp patterns. The last pilot study was a paired comparison of each signal pattern against all the other patterns (for example, the CFR version of the S-O-S was paired with each of the remaining six signals). In any given pairing, both signals were of the same color and the same intensity, so that only the signal pattern differed. For each pairing, subjects selected the signal that they felt was "most conspicuous" and used a rating scale to describe how much more conspicuous it was. In this way the test team identified the best of each class of signal pattern, the "SOS MOD", "4 Hz Group/Interrupt", and "Chirp" (chirp up) (Table 5-2,) for inclusion in the formal lab test. The project eliminated the CFR defined S-O-S.

5.4 Formal Laboratory Test

The objective of the formal lab test was to take the signals that performed best in the pilot studies and determine their relative conspicuities against the Sparse and Moderate backgrounds. The primary difference between the pilot testing and the formal lab test is that the lab test used far more subjects and more precise and objective measures of conspicuity, namely accurate location identification and response time. Study details and results follow.

5.4.1 Test Signals

For the formal lab study, experimenters tested only those signals which performed best in the final pilot study. While the final pilot study specifically determined which flash *patterns* were most conspicuous, the formal lab test considered both pattern and color to determine the most conspicuous *signals*.

The formal lab study used 14 different test signals:

- 4 Hz Group/Interrupt – a train of 4, 4 Hz flashes, a brief pause, then 3, 4 Hz flashes, another brief pause, etc.; presented in each color (cyan, white, and red); total signals = 3.
- 4 Hz Group/Alternating –same flash pattern as the 4 Hz Group/Interrupt, but, the color of the 4-flash group was different than the color of the 3 flash group, yielding a signal that alternated between two colors (cyan-red, white-cyan, or red-white); total signals = 3.
- SOS MOD – a faster variant of the CFR SOS; presented in each color (either cyan, white, or red); total signals = 3.
- Chirp –the pilot study "chirp up;" began with a series of 2 Hz flashes, then a series of 4 Hz flashes, and finally a series of 7 Hz flashes; presented in each color (cyan, white, or red); total signals = 3.
- Chirp-3-color – in this variant, the flash series were different colors (either: 2 Hz red, 4 Hz white, and 7 Hz cyan; or 2 Hz cyan, 4 Hz white, and 7 Hz red); total signals = 2.

Table 5 presents the 14 signal definitions.

Table 5. Signals used in formal laboratory test.

Temporal Pattern	Color	Pattern Description	Actual signal characteristic - milliseconds; parentheses indicate eclipse (off time)
4 Hz Group/interrupt	W	4 Hz 50% duty cycle, 4-3 interrupt	125 (125) 125 (125) 125 (125) 125 (250) 125 (125) 125 (125) 125 (250) …
4 Hz Group/interrupt	R	4 Hz 50% duty cycle, 4-3 interrupt	125 (125) 125 (125) 125 (125) 125 (250) 125 (125) 125 (125) 125 (250) …
4 Hz Group/interrupt	Cy	4 Hz 50% duty cycle, 4-3 interrupt	125 (125) 125 (125) 125 (125) 125 (250) 125 (125) 125 (125) 125 (250) …
SOS MOD	W	46CFR161.013 SOS, quicker flashing	125 (125) 125 (125) 125 (500) 375 (125) 375 (125) 375 (500) 125 (125) 125 (125) 125 (1500) …
SOS MOD	R	46CFR161.013 SOS, quicker flashing	125 (125) 125 (125) 125 (500) 375 (125) 375 (125) 375 (500) 125 (125) 125 (125) 125 (1500) …
SOS MOD	CY	46CFR161.013 SOS, quicker flashing	125 (125) 125 (125) 125 (500) 375 (125) 375 (125) 375 (500) 125 (125) 125 (125) 125 (1500) …
4 Hz group/alt	Cy-R	2-color, 4Hz, 4-3 alternating	**Cy:** 125 (125) 125 (125) 125 (125) 125 (250) **R:** 125 (125) 125 (125) 125 (250) …
4 Hz group/alt	W-Cy	2-color, 4Hz, 4-3 alternating	**W:** 125 (125) 125 (125) 125 (125) 125 (250) **Cy:** 125 (125) 125 (125) 125 (250) …
4 Hz group/alt	R-W	2-color, 4Hz, 4-3 alternating	**R:** 125 (125) 125 (125) 125 (125) 125 (250) **W:** 125 (125) 125 (125) 125 (250) …
Chirp	W	2 Hz/5fl, 4Hz/8fl, 7Hz/15fl	250 (250) 250 (250) 250 (250) 250 (250) 250 (250) 125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (500) ...
Chirp	R	2 Hz/5fl, 4Hz/8fl, 7Hz/15fl	250 (250) 250 (250) 250 (250) 250 (250) 250 (250) 125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (500) ...
Chirp	Cy	2 Hz/5fl, 4Hz/8fl, 7Hz/15fl	250 (250) 250 (250) 250 (250) 250 (250) 250 (250) 125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (500) ...
Chirp-3-color	R-W-Cy	**R**: 2 Hz/5, **W:** 4Hz/8, **Cy**: 7Hz/15, (0.5 sec)	**R:** 250 (250) 250 (250) 250 (250) 250 (250) 250 (250) **W:** 125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125) **Cy:** 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (500) ...
Chirp-3-color	Cy-W-R	**Cy:** 2 Hz/5, **W:** 4Hz/8, **R:** 7Hz/15, (0.5 sec)	**Cy:** 250 (250) 250 (250) 250 (250) 250 (250) 250 (250) **W:** 125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125) **R:** 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (500) ...

Colors: Cy=cyan; R=Red; W=White alt=alternating Hz=Hertz (flashes per second)

5.4.2 Lab Setup

(See general laboratory description in Section 5.2 and Figure 10.) Experimenters tested subjects (observers) individually. Each test subject sat at a small table, and could adjust chair height so their eyes were approximately the same height as the line of test signals and background scene horizon. The distance from the subject's eyes to the center of the screen (with background image and signals) was 20 feet, which kept the accommodation of the eyes at optical infinity (to prevent changes in depth perception during the task which could have increased the response times). The screen and background image provided the subject with a 45^{o} field of view ($\pm 22.5^{o}$ from the central fixation point).

The ambient illumination in the laboratory was representative of a dark night. The measured illuminance without a projected background (clutter) image was 0.00373 lux, darker than a clear night with a quarter- to half-moon (0.01 lux).

5.4.3 Test Subjects

Although the primary "customer" of this distress signal work is intended to be the US Coast Guard search and rescue crews, the project wants a distress signal conspicuous to lay persons, as well. Therefore, our 17 subjects were a diverse group:

- 6 active duty Coast Guard members with current experience in search and rescue;
- 2 Coast Guard Auxiliary members with search and rescue experience;
- 2 Coast Guard civilians with vessel operations experience; and
- 7 civilians with no search and rescue experience.

This group included 14 men and 3 women. Ages ranged from 23 to 74 years; eight subjects were in their 20's (four operational CG and four civilians); of the remaining nine individuals, there were two each in their 30's, 40's, 50's, and 60's, and one person in his 70's.

Project staff tested all subjects with the FrACT[5] test to ensure each had a minimum visual acuity of 20/40. Seventeen subjects were found to have normal color vision using the Pseudo-Isochromatic Plate Ishihara Compatible Color Vision Test[6]. One subject had a known color deficiency; this subject was used to see whether a color-deficient observer would be able to find the test signals.

5.4.4 Experimental Protocol

Upon subject's arrival, one of the test team gave a brief overview of the experiment. Each subject read and signed an informed consent form. One of the test team escorted the subject to a room for the vision tests. After that, the subject returned to the testing laboratory and sat in the dark for 15 minutes to allow his/her eyes to adapt to the dark.

[5] http://michaelbach.de/fract/index.html
[6] http://colorvisiontesting.com/ishihara.htm

An experimenter then instructed the subject on the visual search task they would perform. First, the test team showed the subject examples of the "distress" signals in the test. To ensure the subject could see each signal, experimenters displayed the signals on a uniform gray background. Then, the experimenters presented an example of a sparse background and pointed out background features such as the buoys and colors and intensities of the background lights. Next, a test team member provided the subject training on the search task and the response button panel to indicate when the subject finds the distress signal and in which of seven screen sectors they saw it (Figure 13). Finally, the subject went through ten practice trials (some trials with the Sparse background and others with the Moderate background) to learn how to perform the search task. Note: for training, all signals were in screen location #1.

The test team member told subjects to imagine that they are a part of a search and rescue team, and their job is to locate the distress signal as quickly and accurately as possible. As soon as they were confident that they had located the distress signal, they were to press a "yes" button on the response device. At that point, the distress signal was turned off and a grid was superimposed on the background, dividing it into seven numbered sectors. The subject was to then press the button (1-7) that corresponded to the position where they thought they saw the distress signal. After each trial, a uniform gray screen with a "plus sign" in the middle (a fixation point) replaced the scene background. The test team member also told the subject that on a small proportion of trials, no signal would be displayed. In these trials, the subject was to determine that no signal was present and to press the "no" button on the response device. After that, the uniform gray background with the fixation point replaced the scene background. Each trial lasted a maximum of 60 seconds. If the subject had not responded within 60 seconds, the trial ended and the fixation point replaced the background scene.

5.4.5 Lab Experiment Results

In a signal detection paradigm such as this, there are six different possible outcomes for the set of trials:

<u>Correct Responses</u>
1. Hit – correctly stating that a signal is present and identifying its correct location[7].
2. Correct Rejection – correctly stating that no signal was present, when it actually was not present.

<u>Incorrect Responses</u>
3. False Alarm – stating that a signal was present, when, in fact, no signal was present.
4. Miss – stating that no signal was present, when a signal actually was present.
5. Incorrect Location – stating that a signal was present, but selecting the wrong location.

<u>No Response (Time-Out)</u>
6. Making no response within the 60-second trial window.

Most of the analysis focused on "hits," with some follow-up analysis of "misses".

Response time (the time it takes to find the signal) is an indicator of conspicuity (Wagner and Laxar, 1996): the shorter the response time, the more conspicuous the signal. For this study, analysts only used response times associated with "hits" to calculate the average response time to a given signal.

[7] Experimenters considered a location response "correct" if the location response was the sector in which the signal was located or one sector to either side. E.g., for a signal presented in sector 6, an answer of 5, 6, or 7 would be "correct", while an answer of 1, 2, 3, or 4 would be "incorrect". This compensated for signal locations close to the border between two sectors.

Table 6 shows the average response times associated with each signal-background combination. The left side shows the average response times (RTs) to each signal when seen against sparse background lighting, while the right side shows the average RTs to the same signals against moderate background lighting. For each background, the signals are ordered by increasing response time, i.e., the signal with the shortest RT (i.e., found the fastest) is at the top.

Table 6. Formal Lab Test Results: Mean response times.

Sparse Background			Moderate Background	
Description	**Mean RT**		**Description**	**Mean RT**
4 Hz R	4.04		4 Hz R	6.90
Chirp R-W-Cy	4.46		4 Hz gru-alt Cy-W	8.51
Chirp R	4.77		4 Hz W	9.16
4 Hz gru-alt R-W	4.99		Chirp R	9.21
SOS R	5.69		Chirp W	9.91
4 Hz W	5.79		SOS R	9.97
Chirp Cy-W-R	5.96		4 Hz gru-alt R-W	10.06
Chirp W	6.16		4 Hz gru-alt Cy-R	10.19
4 Hz Cy	6.53		4 Hz Cy	11.28
4 Hz gru-alt Cy-R	6.65		SOS W	11.44
4 Hz gru-alt Cy-W	7.22		SOS Cy	11.57
SOS W	7.73		Chirp R-W-Cy	11.64
Chirp Cy	9.04		Chirp Cy-W-R	12.86
SOS Cy	9.88		Chirp Cy	12.94

R=red, W=white, Cy=cyan gru-alt=group-alternating

Note that the mean response times are substantially longer (by 4.05 seconds on average) against the moderate background than against the sparse background. This corresponds to an average increase of 71%. This demonstrates how an increase in the density of the background lighting (clutter) markedly reduces signal conspicuity.

For signals seen against the sparse backgrounds, the top five signals contained the color red, either alone or in combination with one or two other colors. When asked what made some signals easier to find, many subjects mentioned the color red. Subjects also mentioned that signals that changed color (4 Hz group alt and 3-color Chirp) or flash rates (Chirp and SOS) were easier to find. Some subjects mentioned that cyan signals were harder to see. Note that five of the bottom six signals had a cyan component.

The results against the moderate background are different. Instead of the color red defining the most conspicuous signals, the three signals with fastest response times were 4 Hz signals. On this, subject feedback indicated they liked signals that “didn’t stop”. The 4 Hz signals (both group/interrupt and group/alternating) had only a 250 ms “off” period between the groups of flashes. In contrast, the chirps had a 500 ms “off” period between one chirp and the next, and the SOS signals had a 500 ms “off” period between the letters, plus a 1.5 sec “off” period between one SOS and the next. Subjects stated that they “lost” the signal when it went off. Some subjects mentioned that the 7 Hz component of the chirps was too fast and harder to see than the 2 Hz and 4 Hz components. (Pilot study subjects had remarked that a 7 Hz signal appeared to “shimmer” rather than “flash”; the “shimmer” may have been hard to detect against the

moderate-clutter background.) Importantly, the two 3-color chirps, which yielded relatively fast RTs against a sparse background, yielded relatively slow RTs against the moderate background.
The signal that yielded the best response times against both backgrounds was the 4 Hz red signal – having the two properties (flash frequency and color) of the fastest response time signals against each background separately. In fact, under the sparse backgrounds, the 4 Hz red signal was significantly more conspicuous (i.e., produced significantly faster response times; $p<.05$)[8] than 7 of the other signals. Under the more challenging moderate background, the 4 Hz red signal was significantly more conspicuous than four other signals (and was the only signal to show a significantly faster response time than another).

At the other end of the statistical range, against the sparse background, two of the SOS signals (cyan and white) had response times statistically slower than other signals. The SOS cyan signal produced RTs that were statistically slower than RTs to seven other signals. The SOS white signal had statistically slower RTs than four other signals.

Besides slow response times, another measure of signals with poorer conspicuity is the number of times when a signal was present, but the subject either said no signal was present ("miss") or failed to make a response before the end of the trial ("time-out). Table 7 presents the number of signals "overlooked" (misses + time-outs) by test signal against the sparse (left side) and moderate (right side) backgrounds. In Table 7, the signals are arranged in order of increasing numbers of signals overlooked, with the signals having the least misses and time-outs at the top.

There were very few misses/time-outs against the *sparse* background, considering the experiment presented each signal 6 times to 15 people[9], giving a total of 90 presentations. With the increased clutter of the *moderate* background, the total number of misses and time-outs increased ten-fold. The bottom four signals accounted for 65% of ALL the Misses and Time-Outs under the moderate background. The common element here, they were all *cyan-containing* signals. The three single-color cyan signals (4 Hz Cy, SOS Cy, and Chirp Cy) also had relatively slow response times under both the sparse and moderate backgrounds. By contrast, most of the signals with the least number of misses/time-outs had a *red* component. 4 Hz signals (excluding those with a cyan component), also tended to have few misses/time-outs.

The response time data and the miss/time-out data agree: in this lab test, 4 Hz and red signals were the most conspicuous/most likely to be seen, while cyan signals were the least conspicuous/most overlooked.

[8] $p<.05$ means the *probability* (p) that the 4 Hz red signal was found to be faster solely by chance was <5%
[9] Two subjects were removed from this analysis. The subject with abnormal color vision missed almost as many signals (11) under the sparse background as everyone else combined (14). A second subject had many more time-outs (45) than all other subjects combined (7).

Table 7. Formal Lab Test Results: Misses.

Background:	Sparse	Moderate
Signal	Misses + Time-Outs	Misses + Time-Outs
4 Hz R	0	3
4 Hz gru-alt Cy-R	1	3
4 Hz W	0	5
Chirp R	0	5
Chirp R-W-Cy	0	5
SOS R	0	5
Chirp Cy-W-R	0	5
Chirp W	3	7
4 Hz gru-alt R-W	0	7
SOS W	1	7
4 Hz gru-alt Cy-W	3	18
Chirp Cy	2	23
SOS Cy	0	27
4 Hz Cy	4	27
Total	14	147

R=red, W=white, Cy=cyan gru-alt=alternating

Because of the large numbers of misses/time-outs associated with cyan signals, analysts took a closer look at the data. Considering only misses (signal present, subject responded "no signal"), 15 subjects made 146 misses. Four subjects made 68% of these misses, all of whom were 44-74 years old. These subjects primarily missed the three single-color cyan signals (SOS Cy, 4 Hz Cy, and Chirp Cy) and the 4 Hz alternating Cy-W. As humans age, the lens in the eyes begin to cloud and take on a yellow tint. This is the beginning of a cataract (Beck, 2010). As the lens yellows, it absorbs more of the short-wavelength light rays (blue and cyan), decreasing a person's sensitivity to these colors. Common in people over 40 (Bailey, 2014), this *might* explain some of the decreased sensitivity to cyan signals seen in the older subjects in this study. In fact, the one subject in this age group (44 years old) who did *not* have many misses with the cyan signals was a person who had already had cataracts removed. We did not do any medical screening for cataracts, so analysis cannot make this correlation. However, based on *these* lab results, middle-age and older people *may* have more trouble seeing short-wavelength cyan signals than long-wavelength red signals. When presented a red-cyan combination signal (as the 4 Hz alternating Cy-R signal, or the 3-color chirps) the 44-74 year-old group did not have many misses.

5.5 Lab Study Conclusions

- Response times and correct identifications indicate that 2 Hz and 4 Hz flash rates were most conspicuous. A searcher would be less likely to confuse a 4 Hz-flash signal with common AtoN. Subject input indicated that the 7 Hz flash appeared as a "shimmer" instead of a "flicker."
- Long-wavelength color signals (e.g., red) generally yielded greater conspicuity than white or cyan, even though the lab study matched the colors' apparent brightness. The 4Hz red signal showed the greatest conspicuity of all signals against both sparse and moderate backgrounds.

- Subjects mentioned that variations in color and/or flash frequency were helpful in identifying the signals.
  - The group alternating-color 4Hz signals were conspicuous against both sparse and moderate backgrounds.
  - The 3-color chirps were conspicuous against the sparse background, but not against the moderate background.
  - The red SOS signal was conspicuous against both backgrounds, but not the white or cyan SOS signals. Though color may be the overriding variable, the 0.5 sec "off" periods between the letters and the 1.5 sec "off" periods between one SOS and the next may offset any positive aspect of flash-frequency variation.
- Background clutter has a large effect on conspicuity. Against the moderate background, response times were 71% longer than against the sparse background. Based on the pilot test indications of a need for significantly higher intensity than practicable, the project team did not test signals against substantial background lighting.

The laboratory study identified characteristics for a distress signal that indicated good conspicuity at 6NM against sparse and moderate levels of background clutter. This information became the basis for field testing, in an actual marine environment, to validate the lab findings.

6 FIELD STUDY FOR LED SIGNAL CONSPICUITY AND COMPARISON TO EXISTING SIGNALS

6.1 Overview

To reiterate, the overall project goal is to determine a range of color and temporal patterns that provides a conspicuous signal at 6NM, in 10 miles visibility.

In broad terms, the field study would begin where the lab study left off: compare human response to different LED color and flash patterns to determine conspicuity, and include two commercial, off-the–shelf devices and a hand-held pyrotechnic flare.

An original target was to test for characteristic-based signal conspicuity against multiple background lighting clutter conditions: "substantial," "moderate," and "sparse." After lab testing and discussions with project sponsors, the project team and sponsors concurred on limiting trials to evaluation against sparse conditions only, due to both the excessively large number of trials necessary to evaluate in multiple conditions, and derived, signal-intensity requirements that would put such a signal well outside the range of presently-available, commercial off the shelf devices (understanding that LED technology is improving at a quick pace).

In the lab, background-lighting clutter in the marine environment from Sandy Hook made up the scenery. For the field study, project leads determined that an alternative location, Eatons Neck, New York offered an equivalent range of "sparse" and "moderate" background lighting clutter conditions, but, since the site is actually a Coast Guard Station, has vastly improved logistics capability for conducting the field study. This location also provided an approximate 10-foot (and greater) height of eye AWL for observers to view signals displayed from vessels at 6NM.

The premise of the field test experimental design was to display a signal from a vessel in one of two possible sectors on the horizon (with relatively the same concentration of background lighting clutter), have observers determine whether they identified the signal in one sector or the other, or not at all (similar to the lab testing) and record the observers' response time. This captured two indices of conspicuity: the percentage of correct signal detections, and the response time to detect a signal.

Field testing required by this project required the use of human subjects in the research. Test protocols were reviewed by the RDC IRB and were approved in compliance with COMDTINST M6500.1.

6.2 Field Study Signal Generator

In the same way the project designed LED signal generators for the lab testing, to test unique signals in the field, the project required custom LED signal generators that were weatherproof, and that could allow a number of signal displays, visible at 6 miles.

The signal generators produced various flash patterns in any of seven colors, at nominal intensities from 80 to 4000 cd, within a relatively narrow field-of-view (20 degrees). For the field testing, a short pilot effort showed that intensities from 80-400 cd would suffice. Table 8 shows the specified and measured LED chromaticities, while Table 9 indicates the actual, measured photopic intensities for each color and nominal intensity, for each of the two signal generators.

In order to allow flexibility for multiple test signal characteristics, the test signal generator uses a microprocessor to generate/control the LED. This allowed us to vary the timing, color combinations and intensity of the signals. Controlling intensity digitally (by the microprocessor) means that intensity level adjustment will be in discrete steps, and, as shown in Table 9, the actual intensities are somewhat different than the "nominal" values, with the difference being larger at the lower intensities. The reason for this is: the range of intensity adjustment from 0 through 4000 cd is broken down into equal increments; a step change of one increment at the lower intensities effects a greater percentage change on the signal than it does at the higher intensities. During calibration in the photometric lab, each of the 7 LED arrays (one array for each color) was calibrated to have a luminous intensity as close to the nominal value as possible.

Table 8. Signal generator LED characteristics.

LED Color	Specified, Dominant Wavelength or Color Temperature	Tolerance	Measured Values Signal Head 2 (G-2)	Measured Values Signal head 3 (G-1)
White	4000K	3710K-4260K	4762	4719
Blue	470nm	460-485nm	474	474
Cyan	505nm	490-515 nm	504	504
Green	530nm	520-540 nm	522	522
Amber	590nm	584-594 nm	591	590
Red-Orange	617nm	610-620 nm	615	614
Red	627nm	620-645 nm	621	621

Table 9. Signal generator actual intensities in cd.

Signal Intensity Unit 2 (West Boat)							
Nominal	Red	Red-Orange	Cyan	Green	Blue	White	Amber
80	50	61	55	43	37	61	80
100	116	139	112	95	132	138	122
200	182	212	202	199	227	216	213
400	421	434	412	412	422	434	411
Signal Intensity - Unit 3 (East Boat)							
Nominal	Red	Red-Orange	Cyan	Green	Blue	White	Amber
80	47	53	36	50	80	78	57
100	126	129	121	107	130	93	133
200	207	208	204	222	232	181	204
400	377	428	418	404	430	363	416

As mentioned in the discussion on lab testing, the project team used the lab results and subjective input to further refine signal characteristics, particularly the nature of the temporal flash patterns for the SOS and chirp patterns, reducing the "off" times between chirps from 0.5 sec to 0.25 sec, and reducing the off-times between both the components and one SOS to the next to 0.375 sec.

To better evaluate the appropriate frequency range for good conspicuity, the project added 2 Hz and 6 Hz signals. Testing included six LED colors and white (Table 8 & Table 9) to evaluate color conspicuity in actual atmospheric conditions. Table 10 indicates the available signal patterns for field testing. Of the field test signals, three were identical to lab signals: 4Hz group/interrupt in white, red, and cyan.

For the field testing, experimenters mounted the signal generator signal head (Figure 15) on a "mast" with rudimentary aiming capability (Figure 16). The mast allowed vertical placement of the signal head, 10 feet (or more) AWL.

In both the lab testing and the field testing, the test team tried to replicate conditions where the signal would appear on or close to the subject's horizon, in the same geographic direction as background lighting clutter.

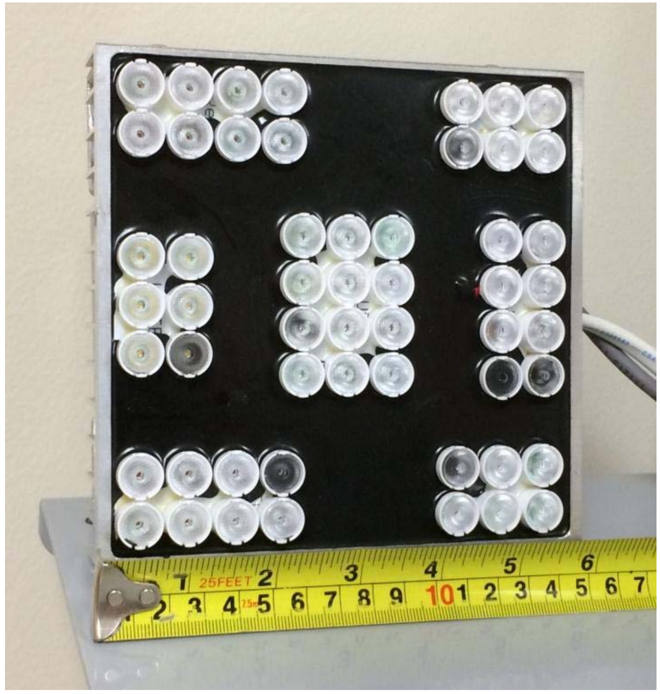

Figure 15. Signal generator signal head.

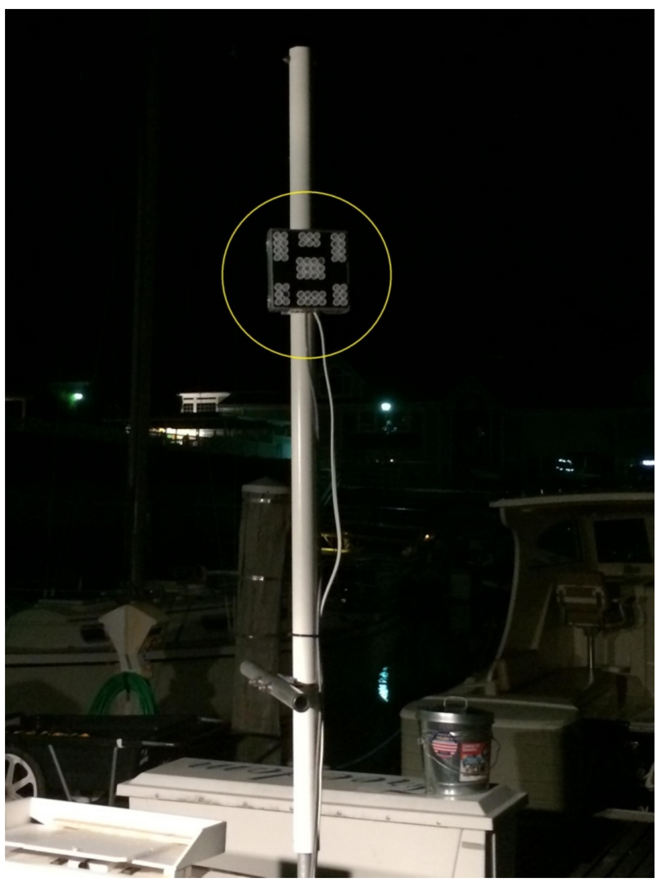

Figure 16. Signal head mounted on stern of signal vessel.

Table 10. Field study available signal generator patterns (pre-programmed).

Temporal Pattern	Color*	Pattern Description	Actual signal characteristic - milliseconds; parentheses indicate eclipse (off time)
4Hz	single	Continuous 4Hz signal 50% duty cycle	125 (125) 125 (125) 125 (125) …
4 Hz alternating	Two-color	2-color, 4 Hz 50% duty cycle, 1-1 alternating	**color A**: 125 (125) **color B**: 125 (125) **color A**: 125 (125) **color B**: 125 (125) …
4 Hz Group/interrupt	single	4 Hz 50% duty cycle, 4-3 interrupt (same as lab)	125 (125) 125 (125) 125 (125) 125 (250) 125 (125) 125 (125) 125 (250) …
4 Hz Group/Alternating	Two-color	2-color, 4Hz 50% duty cycle, 4-3 alternating (same as lab)	**color A**: 125 (125) 125 (125) 125 (125) 125 (250) **color B**: 125 (125) 125 (125) 125 (250) …
SOS Mod (field)	single	SOS, less eclipse time than lab	125 (125) 125 (125) 125 (125) 375 (125) 375 (125) 375 (125) 125 (125) 125 (125) 125 (250) …
"Chirp" (Field)	single	2 Hz/5fl, 4Hz/8fl, 6Hz/15fl ; all 50% duty cycle	250 (250) 250 (250) 250 (250) 250 (250) 250 (250) 125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (250) …
3-color "Chirp" (Field)	Tri-color	Color A: 2 Hz/5fl, Color B: 4Hz/8fl, Color C: 6Hz/15fl ; all 50% duty cycle	**Color A**: 250 (250) 250 (250) 250 (250) 250 (250) 250 (250) **Color B**: 125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125)125 (125) **Color C**: 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (71.4) 71.4 (250) …
2 Hz – 25%	single	Continuous 2Hz signal 25% duty cycle	125 (375) 125 (375) 125 (375) …
2 Hz – 50%	single	Continuous 2Hz signal 50% duty cycle	250 (250) 250 (250) 250 (250) 250 (250) …
2 Hz – 25 Group/alt	Two-color	2-color, 2Hz 25% duty cycle, 4-3 alternating	**Color A**: 125 (375) 125 (375) 125 (375) 125 (250) **Color B**: 125 (375) 125 (375) 125 (250) …
2 Hz – 50 Alternating	Two-color	2-color, 2Hz 50% duty cycle, 4-4 alternating	**Color A**: 250 (250) 250 (250) 250 (250) 250 (250) **Color B**: 250 (250) 250 (250) 250 (250) 250 (250)…
6 Hz	single	Continuous 6Hz signal 50% duty cycle	83.3 (83.3) 83.3 (83.3) 83.3 (83.3) 83.3 (83.3) 83.3 (83.3)…
Fixed	single	Continuous signal	Continuous signal (if PWM, frequency >100Hz)

Color* indicates whether a pre-programmed signal accepts a single color or more than one color at operator key-in

fl = flashes

6.3 Field Study Location

CG Station Eatons Neck, NY provides an unobstructed view with a variety of background lighting clutter (Connecticut shore), an unobstructed horizon view, and allowed for locating approximately 15-25 subjects, a 10 person test team, test control and communications trailer in close proximity to electrical power, and sanitation.

The location's proximity to Huntington Bay and Northport Harbor allowed the test team to base signal vessel activity in close proximity of the shore-based experiment team. This facilitated technical interaction among the various team members for equipment issues and logistics.

Of even additional benefit, the test site was approximately mid-way between two environmental buoys that allowed archival data retrieval.

Figure 17 is a nautical chart (NOS 12363) excerpt with observer location, "sectors" with sparse background lighting (heavier red and blue lines approximate a 6NM arc from the observers), and environmental buoy locations.

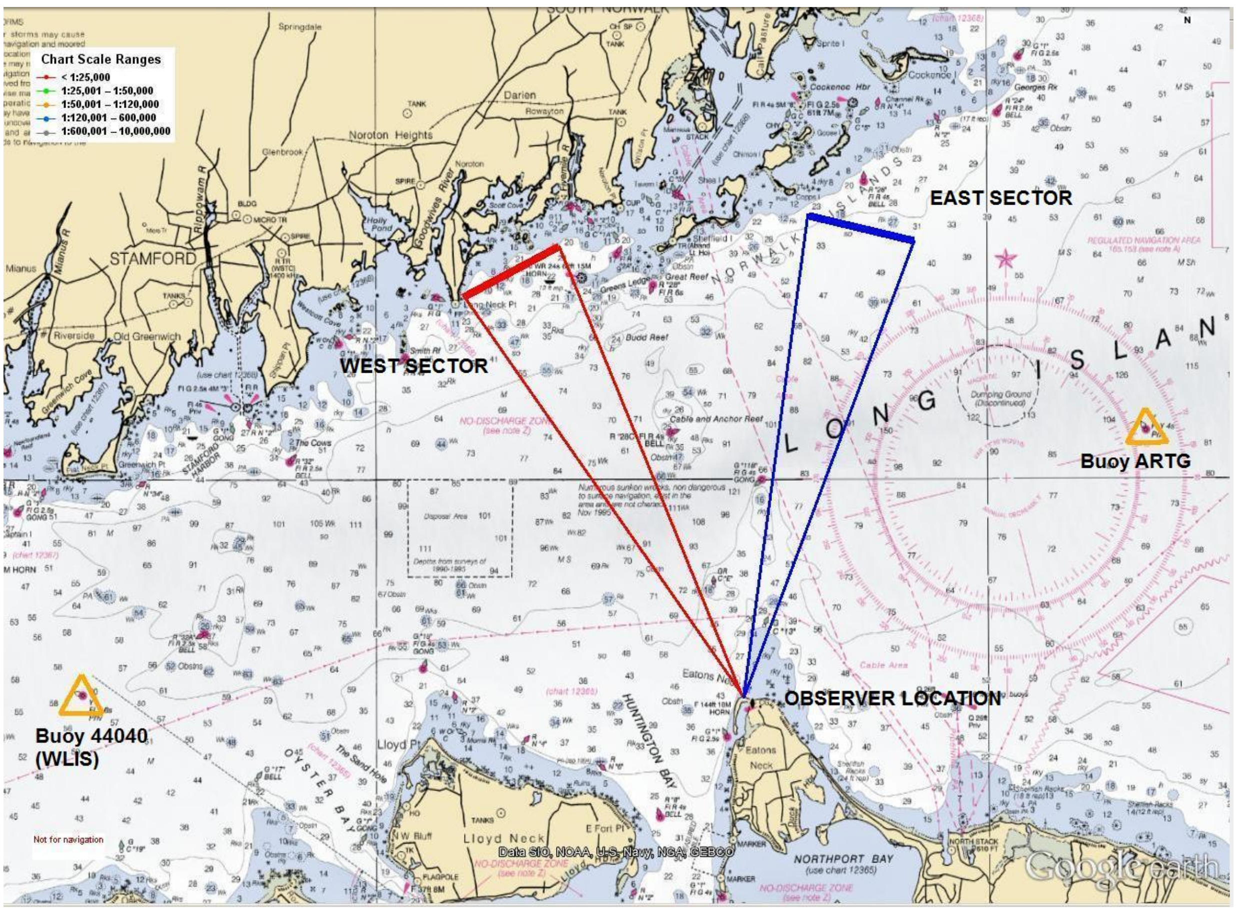

Figure 17. Field Test Siting; CG Station Eatons Neck and "sparse" background clutter sectors and environmental buoy locations.

Figure 18 shows approximate viewer location at CG Station Eatons Neck, while Figure 19 shows how "sparse" background lighting clutter appears from the observer location.

Figure 18. Eatons Neck Point viewing location, viewing height of eye marked in red.

Figure 19. Sparse background clutter viewed from Eatons Neck Point.

Because the goal of the project is to identify signal characteristics visible at 6 NM at 10 miles meteorological visibility, the project team determined the distances to various landmarks and aids to navigation so as to have indicators of the actual visibility at the beginning of each night's testing, and indicators so as to quickly identify if visibility changed during the course of a test. Table 11 lists the landmarks, ranges, and bearings, while Figure 20 shows representative distances from Eatons Neck Point to landmarks across Long Island Sound. The landmarks allowed for easy estimation of observed visibility and rapid identification of changes in visibility.

Table 11. Distance reference table for visibility estimation.

From	To	Dist (NM)	Bearing (M)	Characteristic
Eatons Neck Pt	Buoy 11B	2.8	17	Fl G 4s
Eatons Neck Pt	Cable & Anchor 28C	3.4	358	Fl R 4s
Eatons Neck Pt	Manresa Is Stack	7.1	369	Red Fl
Eatons Neck Pt	Cockenoe Red	7.3	19	Fl R 4s 5M
Eatons Neck Pt	Cockenoe Green	7.5	24	Fl G 2.5 7M 61Ft
Eatons Neck Pt	Stamford	8.7	325	City
Eatons Neck Pt	WNLK tower	9.8	364	Red Fl
Eatons Neck Pt	Penfield Reef Lt	12.7	53	FL R 6s 51ft 15M
Eatons Neck Pt	Black Rock Gas Plant	14.9	48	Whi Hi Inten Fl
Eatons Neck Pt	Bridgeport Hbr Sta	16.2	50	Red Fl
Eatons Neck Pt	Tall Bldg, White Plains	17.2	293	Lighted Building
Eatons Neck Pt	New Haven Hbr Sta	29.8	62	Red Fl
Center of East Arc	Buoy 11B	3.3	214	Fl G 4s
Center of East Arc	Cable & Anchor 28C	3.4	237	Eatons Neck Pt
Center of East Arc	Northport Stacks	7.7	185	Red Fl
Center of East Arc	Penfield Reef Lt	7.7	74	FL R 6s 51ft 15M
Center of East Arc	Stratford Shoal Lt	12.1	102	FL 5s 60ft 13M
Center of East Arc	Old Field Pt. Lt	12.2	135	Alt RG 24s 74ft 14M
Center of East Arc	Port Jeff Stacks	14.5	129	Red Fl
Center of West Arc	Northport Stacks	8.9	157	Red Fl
Center of West Arc	Old Field Pt. Lt	15.9	118	Alt RG 24s 74ft 14M
Center of West Arc	Port Jeff Stacks	18.2	122	Red Fl

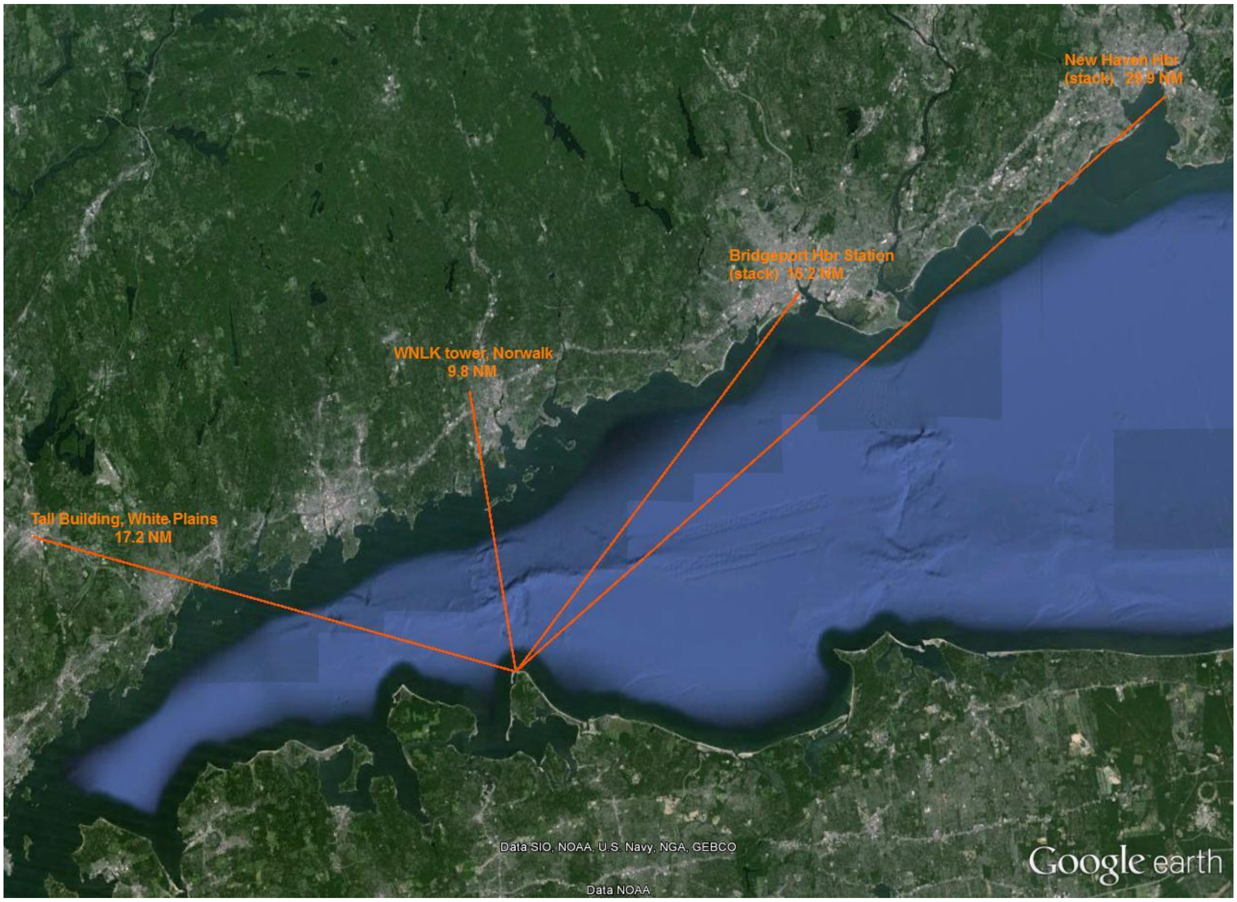

Figure 20. Representative distances for estimating visibility.

6.4 Field Study Pilot Testing

On the evenings of 25-26 August 2014, the project team conducted pilot testing to make sure: 1) the signal generators worked properly, 2) that shoreside observers could readily view and identify the signals at 6NM range, 3) target vessel locations with respect to background lighting conditions provided the proper background lighting conditions, and 4) that experimenters could effectively communicate between vessels and the shore, allowing full coordination of target vessel positioning and signal display.

The project used one vessel, transiting to both location arcs in the pilot testing. During both nights, the observed visibility was greater than 20 NM.

The first testing required the signal boat to station itself in one of the two sector areas at 6 NM range, display a series of signals, and then move to the other sector area and do the same (Figure 21). On 25 August, the signal vessel began displaying signals at 400 cd at a 4Hz continuous flash for all colors. Project team members easily identified all signals and colors from the signal generator, so study leads decided to continue signal testing for the same sequence at 200 cd. Testing also included a few multi-color signals (group alternating and chirp) at 200 cd, again, with shore-based team members readily identifying them.

In considering the background lighting clutter, the "sparse" conditions did include some potential "distracters" (as modeled in the lab), including lighted buoys, lighthouses (one prominent and two not-so-prominent), towers

and stacks with flashing lights, and other sources (e.g. vehicles with flashing lights). As these are all items that a searcher might experience, the shore team noted that when stationing the signal vessel, test controllers should try not to have the signal appear directly in line with one of the extraneous sources, or one of the individual background lights in what Yeager (IALA, 2010) terms "locally substantial" clutter.

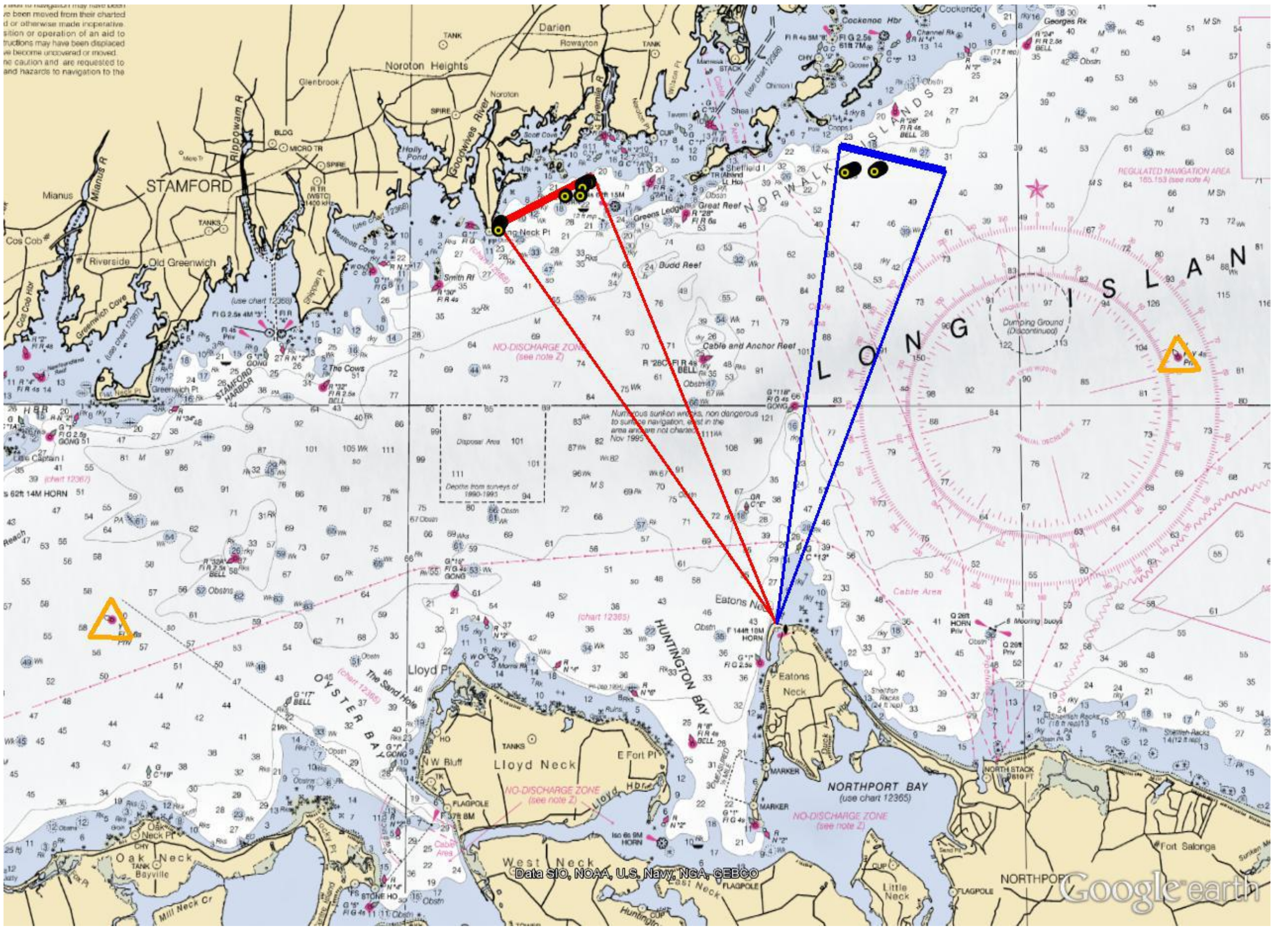

Figure 21. Locations of signal boat during pilot testing, 25-26 Aug 2014

On the second night, the vessel displayed a first set of trials at 200 cd. For each color, test team members looked at 6 Hz, 4 Hz, 2 Hz 50% duty cycle, and 2 Hz 25% duty cycle. Additionally, observers viewed two COTS items, one in both "flash" and "flicker" modes. The vessel signal crew also ignited a hand-held flare to ensure they could activate it and extinguish it, at the appointed times, without "bleed-over" visible to the observers.

The testing then tried multi-color signals at 200 cd, including 4 Hz group alternating combinations, the blue Chirp, and two Chirp-3-color signals. The observers easily identified all these signals. Finally, experimenters compared three SOS signals at both 200 cd and 100 cd. Though visible, observers said they had more trouble seeing the 100 cd signals than the 200 cd signals.

The major take-away from the field study pilot testing was that for the actual field study, though test team shore personnel could discern signals at 6 NM with 100 cd signal intensity, testing would start with 200 cd nominal signal intensity, a level well above a subject's detection threshold.

6.5 Field Study Planning and Experimental Procedures

Under the overall project goal of providing a conspicuous distress location signal characteristic, the project built three objectives into the field study experiment test plan:

- Validate the lab study color downselect and overall lab results in the field.
- "Refine" the temporal frequency range for the base frequencies--6 Hz replaced 7 Hz in the chirp--and, reduce the eclipse periods between SOS components, consecutive SOS signals, and consecutive Chirp signals.
- Determine "best" signal color/pattern combos and compare with commercial off-the-shelf (COTS) devices and hand flares.

With location, signal generator, and general procedures in order, the time and budget limitations required experiment planners to apply certain constraints to the actual experimental procedures. In the lab testing, the project ran 17 subjects through 179 trials, one at a time, over 9 days, during "normal working hours," in controlled conditions. For the field study, subject to actual darkness, weather, and "late" hours, in an effort not to discourage potential volunteers, the team planned for individual tests to last no more than 120-150 minutes. With an additional 30-45 minutes of preliminary instruction and "practice" trials, 15 minutes for a break in the middle of the trials, and 10 minutes to "stand-down" after a test period, this required volunteers to spend approximately 3 hours on site. This time limitation resulted in a target of 60-70 trials per test. In turn, this limitation forced experiment planners to be judicious in weighing the number of signals displayed against the number of opportunities for the subject to view a particular signal. Each test had 64 trials.

Schedule constraints required field study completion in mid-September. The testing would cover four nights, with subjects participating in separate, 8-signal tests each night.

The project established a target subject pool of 20-25 for each night, and the project manager specifically encouraged subjects to participate on multiple nights. The test subjects were a mix of Coast Guard civilians, Coast Guard Auxiliarists, and U. S. Power Squadron members, all volunteers for the effort. Eight subjects participated in all four tests (from 36% to 53% of the participants for each test). All subjects provided "informed consent" to participate.

At the beginning of each test, project leads briefed participants on the nature of the experiment, the use of the response devices, and ran participants through a series of "practice" trials so as to familiarize participants with signal appearance, approximate signal vessel location, response key use, experiment methods, and trial timing.

Each trial proceeded as follows. An experimenter would alert subjects to begin looking for a potential signal (in most trials one of the two vessels displayed a signal, but in 25% of the trials, neither vessel displayed a signal (catch trial)). Subjects then had the opportunity to scan the two sectors for a signal. A test-vessel crew then displayed a signal (approximately three to five seconds after the "trial start" announcement) for 30 seconds. As soon as each subject was sure they had detected a signal, they were to press the appropriate response key to indicate whether the signal was on the right (east) or left (west). If the subject did not see a signal, they pressed a different key. An experimenter would then tell the subjects when the trial ended (i.e., immediately after the vessel crew extinguished the signal). After the first half of the trials were completed, subjects were given a fifteen-minute break. The entire test took approximately 120-150 minutes.

6.6 Results Analysis Description

For each test, the evaluation metrics were:

1) correct vs. incorrect: if the experimenters displayed a signal, did the subject correctly identify which side it was on; or, if the experimenters did not display a signal, did the subject correctly respond that no signal was present.

2) response time: the elapsed time between the signal initiation and subject response.

These types of data tend to be skewed, rather than normally distributed (i.e., not centered about a mid-point on a bell-shaped curve). Because of this, "nonparametric tests" are appropriate analytic tools.

For each night's test (group of "trials"), analysts calculated a mean RT to each signal, for each subject, for those trials which the subject gave a correct response. Since not all subjects got every trial correct, these means were based on different numbers of correct responses across participants. As the summary result tables in Section 6.7 show, the record includes a "no response" category. One could assume that the subject just did not see the signal, but it is possible that some "no responses" occurred for other reasons: perhaps a subject stooped to tie their shoe, dropped their response device, or didn't press the response key firmly enough. In the results, if a subject DID respond, but either BEFORE or AFTER the experimenters displayed a signal, analysts also counted these as "no response." The results DO include this "no response" value, but do not include it in the total to determine the "mean % correct" responses in the analysis.

The analysts used a Friedman nonparametric test for repeated measures design (Siegel, 1956). This test determined whether there were any significant differences among the entire set of data being analyzed within a test (for example, whether mean RT to any of the eight signals is significantly different from the rest). If the Friedman test indicates a significant difference, analysts used a Wilcoxon test to determine which specific mean RTs were significantly different from others.

The Wilcoxon test is somewhat conservative, which benefits this analysis. Due to the large number (28) of follow-up comparisons between pairs of the eight signals (a less-conservative test would be more likely to consider a difference as "significant" when it might have been due to chance). The Wilcoxon nonparametric test makes use of both the actual values (e.g., mean response times and mean percent correct scores) and their ordinal relationships (rankings of the scores between pairs of signals) to draw conclusions. This hybrid approach, using rankings of quantitative/parametric data, provides greater statistical power to identify differences (Runyon & Haber, 1967).

Each test analysis includes Wilcoxon tables to highlight differences between signal response times, and indicates those pairs that differed at the following levels of significance:

+ $p < 0.01$ (shown as dark red shading, white numbers, **)

+ $p < 0.05$ (shown as dark red shading, white numbers, *)

+ $p < 0.10$ (shown as medium pink shading)

+ $p > 0.10$ (= non-significant, or ns—unshaded in tables)

where "p < 0.01" indicates there is less than a 1% probability that the RT differences are due to chance, while "p < 0.10" indicates there is less than a 10% probability that the RT differences are due to chance. Though statistical convention usually indicates a level of "significance" at p<.05, the analysis includes other p-values to indicate potential trends in the significance of response-time differences.

6.7 Field Study Execution and Results

6.7.1 Test 1 – Validate Color Downselect and Lab Rankings – Monday 15 September 2014

Test 1 had three aspects. (1) By presenting all seven LED colors (as 4-Hz Group Interrupt signals), the analysis may be able to deduce the emphasis of color alone on conspicuity. (2) The lab testing used paired/multiple comparisons to reduce signal colors to three (red, white, and cyan); the field trials validate whether red-orange actually is comparable to red, amber to white, and whether cyan actually performed as well as blue or green (comparisons can indicate the degree of color-range equivalence). (3) Validate the overall lab findings: i.e., whether field trial results indicate relative performance similar to the lab. The field study used three signals for this: 4-Hz Group Interrupt Red, by response time, the most conspicuous in the lab, 4-Hz Group Interrupt White, the middle of the lab stimuli, and 4 Hz Group Alternating Cyan-White, with lab response times in the longest quartile (least conspicuous).

Table 12. Test 1, Signals.

Pattern	Color	Nominal Intensity	# Trials
4-Hz Group/Interrupt	Red	200cd	6
4-Hz Group/Interrupt	Red-Orange	200cd	6
4-Hz Group/Interrupt	Amber	200cd	6
4-Hz Group/Interrupt	White	200cd	6
4-Hz Group/Interrupt	Green	200cd	6
4-Hz Group/Interrupt	Cyan	200cd	6
4-Hz Group/Interrupt	Blue	200cd	6
4-Hz Group/Alternating	Cyan/White	200cd	6
No Signal	--	-	16

Test 1, the color downselect validation, used signals with the same, 4Hz group-interrupt pattern at 200 cd nominal signal intensity (Table 12), at approximately 4.2 to 4.7 NM.[10]

[10] Appendix B includes detailed environmental information and vessel position data for each test/test segment.

Table 13. Test 1, Results summary (19 Subjects).

Test 1 - Color Downselect Validation by % correct and Mean Response Time (RT) (seconds)							
Signal	**Mean correct**	Mean RT	No Response	Signal	Mean correct	**Mean RT**	No Response
Blue	**100%**	5.68	1%	Blue	100%	**5.68**	1%
Cyan	**99%**	5.79	0%	Cyan	99%	**5.79**	0%
Red-Orange	**97%**	6.32	0%	Red-Orange	97%	**6.32**	0%
Green	**96%**	6.44	2%	Green	96%	**6.44**	2%
Red	**96%**	6.58	3%	Red	96%	**6.58**	3%
Amber	**96%**	8.64	1%	White	95%	**7.65**	2%
White	**95%**	7.65	2%	Amber	96%	**8.64**	1%
Test 1 - Lab Ranking Validation by % correct and Mean Response Time (RT) (seconds)							
Signal	**Mean correct**	Mean RT	No Response	Signal	Mean correct	**Mean RT**	No Response
Cy-Whi-Alt	**100%**	6.92	0%	Red	96%	**6.58**	3%
Red	**96%**	6.58	3%	Cy-Whi-Alt	100%	**6.92**	0%
White	**95%**	7.65	2%	White	95%	**7.65**	2%

Table 13 presents the mean RTs and mean percent correct for the tested signals. Table 14 presents the RT comparisons by signal pairs (Wilcoxon analysis) for these signals.

Table 14. Test 1, Wilcoxon analysis.

Test 1-Wilcoxon Analysis - Response time (RT) Statistical Comparison								
Signals	**Avg RT**	Blue	Cyan	Red-Or	Green	Red	White	Yellow
Blue	5.68	-----	74	64	66	46*	27**	15**
Cyan	5.79		-----	68.5	69	53	33*	14**
Red-Orange	6.32			-----	94	82	55	17**
Green	6.44				-----	84.5	55	25.5
Red	6.58					-----	61	26**
White	7.65						-----	55.5
Amber	8.64							-----
N=19	□ not significant		□ p<.10		□ p<.05*	□ p<.01**		

- the mean RT to blue was fastest, though not statistically different from the mean RT to cyan, red-orange, or green.
- the mean RT to Cyan was almost equivalent to the mean RT to blue
- the mean RT to amber was significantly longer than the mean RTs to all colors except white
- the mean RT to white was also statistically longer than to blue and to cyan
- the mean RT to red was also statistically longer than to blue

Multiple participants indicated they thought blue "stood out" better than any other signal. Of note, two of the participants implied that they didn't really know which color cyan was. With almost equivalent fast response times to blue and cyan, their conspicuity is good.

The relatively slow response times to white and amber coincide with comments from the test subjects that indicated the white and amber distress signals looked like just another background light on shore, most of which were varying shades of yellow to white. This shows how colors that differ from the predominant background lighting yield greater conspicuity.

In comparing field test response times to lab results (validation of lab test procedures), the relative order of the signals did not agree. One distinction between the lab test signals and the field test signals is that for the lab testing, the test procedures used subjective "brightness matching," to determine the amount of intensity each color would produce, while field test procedures used nominally equal intensities for all colors displayed in all signals. This methodological distinction, combined with the effect of real-world atmospherics may explain the differences between lab results and field test results.

6.7.2 Test 2 - Validate Frequency Downselect, Compare Frequency Conspicuities, and Check Signal Modifications Tuesday - 16 September 2014

Test 2 looked at different signal patterns, mainly blue in color, to determine whether flash frequency had any basis in varying RTs (Table 15). In addition to 2Hz, 4Hz and 6Hz, testing included 2 signals, "chirps," that combined the three frequencies (one using 2Hz blue, 4Hz red-orange, and 6Hz cyan, the other chirp was blue at all 3 frequencies), an SOS (4 Hz – 2 Hz – 4 Hz), a 4Hz alternating-color signal (blue and red-orange), and a 4Hz red, group-interrupt, the signal with the shortest mean RT from lab testing.

As with Test 1, initial signal distance was 6 NM. Since observers could not see the signals, despite visibility > 20 NM, the signal vessels moved closer until the observers could readily discern a 400 cd signal. Note. One vessel's location data recorder failed part way into test two, so distance is from vessel's navigation equipment and test director logs.

Throughout Test 2, signal distances were between 4.7 and 5.1 NM from the subjects. Testing started at a nominal flash intensity of 200 candela (cd), but subjects almost always identified all signals with RTs faster than in Test 1. After 32 trials experiment leads lowered the nominal flash intensity to 100 cd for a second set of 32 trials (Table 16).

Table 15. Test 2, Part 1 - Signals.

Pattern	Color	Nominal Intensity	# Trials
4 Hz Group Alternating	Blue/ Red-Orange	200cd	3
2 Hz 25% Duty Cycle	Blue	200cd	3
6 Hz	Blue	200cd	3
Chirp-3-color	Blue/ Red-Orange/Cyan	200cd	3
Chirp	Blue	200cd	3
2 Hz 50% Duty Cycle	Blue	200cd	3
SOS-Mod	Blue	200cd	3
4 Hz Group Interrupt	Red	200cd	3
No Signal	-	-	8

Table 16. Test 2, Part 2 - Signals.

Pattern	Color	Nominal Intensity	# Trials
4 Hz Group Alternating	Blue/ Red-Orange	100cd	3
2 Hz 25% Duty Cycle	Blue	100cd	3
6 Hz	Blue	100cd	3
Chirp-3-color	Blue/ Red-Orange/Cyan	100cd	3
Chirp	Blue	100cd	3
2 Hz 50% Duty Cycle	Blue	100cd	3
SOS-Mod	Blue	100cd	3
4 Hz Group Interrupt	Red	100cd	3
No Signal	-	-	8

Table 17 presents the mean RTs and mean percent correct for the signals in Test 2, Part 1. Table 18 presents the RT comparisons by signal pairs (Wilcoxon analysis) for these signals.

Table 17. Test 2, Part 1 - Results summary (22 Subjects).

Test 2 - Part 1 - Pattern at 200 cd, by % correct and Mean Response Time (RT) (seconds)									
Signal Pattern	Color	**Mean Correct**	Mean RT	No Repsonse	Signal Pattern	Color	Mean Correct	**Mean RT**	No Repsonse
SOS-Mod	BL	**100%**	3.71	0%	SOS-Mod	BL	100%	**3.71**	0%
2 Hz 50% duty cycle	BL	**100%**	3.94	0%	Chirp, 3-color	BL/RO/CY	98%	**3.87**	0%
4 Hz Group Alt	BL/RO	**100%**	3.95	0%	2 Hz 50% duty cycle	BL	100%	**3.94**	0%
6 Hz	BL	**100%**	3.97	0%	4 Hz Group Alt	BL/RO	100%	**3.95**	0%
Chirp	BL	**100%**	4.25	0%	6 Hz	BL	100%	**3.97**	0%
2 Hz 25% duty cycle	BL	**100%**	4.46	0%	Chirp	BL	100%	**4.25**	0%
Chirp, 3-color	BL/RO/CY	**98%**	3.87	0%	2 Hz 25% duty cycle	BL	100%	**4.46**	0%
4 Hz Group Int	R	**98%**	4.96	0%	4 Hz Group Int	R	98%	**4.96**	0%
BL= Blue, CY=Cyan, R=Red, RO=Red-Orange; Alt=alternating, Int=Interrupt									

- Subjects correctly responded to all signals in 98-100% of the trials (Table 17). There was no case where a subject failed to respond to a signal.
- The mean response times to all signals were relatively fast and within a small range, 3.71 seconds to 4.96 seconds (Table 17).
- The Wilcoxon analysis (Table 18) indicates RTs to the 4 Hz Red as significantly slower than to five signals and tending slower to a sixth.
- The RTs to the 2Hz 25% duty cycle signal were significantly slower than to the RTs to the 3-color chirp, and tending slower to the SOS Mod and 2Hz 50% duty cycle signals.
- RTs to six signals were faster and not statistically different from each other. These were: SOS Mod, 3-color Chirp, 2 Hz 50% duty cycle, 4 Hz group-alternating-color, 6 Hz, and the blue-only Chirp.
- Overall, because of the fast response times, correct responses, and the lack of “no response,” at the nominal 200 cd intensity, all the signals were relatively conspicuous.

Table 18. Test 2, Part 1 - Wilcoxon analysis.

Test 2, Part 1 - Wilcoxon Analysis - Response time (RT) Statisitical Comparison									
Signals	**Avg RT**	SOS Mod - Blue	3-color Chirp	2 Hz 50% Blue	4 Hz Gru Alt Blue/Red-O	6 Hz Blue	Chirp Blue	2 Hz 25% Blue	4 Hz Gru Int. Red
SOS Mod - Blue	3.71	-----	107	100	113	98	87	62	39**
3-color Chirp - Blue/Red-O/Cyan	3.87		-----	111	103	96.5	83	37**	37**
2 Hz 50% Duty Cycle - Blue	3.94			-----	102	109	98	65	52*
4 Hz Group Alt - Blue/Red-Orange	3.95				-----	96	91	72	54*
6 Hz - Blue	3.97					-----	83	109	48*
Chirp - Blue	4.25						-----	86	63.5
2 Hz 25% Duty - Blue	4.46							-----	79
4 Hz Group Interrupt - Red	4.96								-----
N = 21	☐ not significant		☐ p<.10		☐ p<.05*	☐ p<.01**			

Table 19 presents the mean RTs and mean percent correct for the signals in Test 2, Part 2. Table 20 presents the RT comparisons by signal pairs (Wilcoxon analysis) for these signals.

Table 19. Test 2, Part 2 - Results summary (21 Subjects).

Test 2 - Part 2 - Pattern at 100 cd, by % correct and Mean Response Time (RT) (seconds)									
Signal Pattern	Color	**Mean Correct**	Mean RT	No Repsonse	Signal Pattern	Color	Mean Correct	**Mean RT**	No Repsonse
4 Hz Group Alt	BL/RO	**100%**	4.33	0%	4 Hz Group Alt	BL/RO	100%	**4.33**	0%
Chirp, 3-color	BL/RO/CY	**97%**	4.79	0%	6 Hz	BL	97%	**4.37**	0%
6 Hz	BL	**97%**	4.37	0%	SOS-Mod	BL	97%	**4.69**	0%
SOS-Mod	BL	**97%**	4.69	0%	Chirp	BL	97%	**4.75**	0%
Chirp	BL	**97%**	4.75	0%	Chirp, 3-color	BL/RO/CY	97%	**4.79**	0%
4 Hz Group Int	R	**97%**	5.59	0%	2 Hz 25% duty cycle	BL	94%	**4.89**	0%
2 Hz 25% duty cycle	BL	**94%**	4.89	0%	2 Hz 50% duty cycle	BL	94%	**5.55**	0%
2 Hz 50% duty cycle	BL	**94%**	5.55	0%	4 Hz Group Int	R	97%	**5.59**	0%
BL= Blue, CY=Cyan, R=Red, RO=Red-Orange; Alt=alternating, Int=Interrupt									

Table 20. Test 2, Part 2 - Wilcoxon analysis.

Test 2, Part 2 - Wilcoxon Analysis - Response time (RT) Statisitical Comparison									
Signals	Avg RT	4 Hz Alt Blue/Red-O	6 Hz Blue	SOS Blue	Chirp Blue	3-color Chirp	2 Hz 25% Blue	2 Hz 50% Blue	4 Hz Int. Red
4 Hz Alt - Blue/Red-Orange	4.33	-----	94	112	76	73	66	42**	52*
6 Hz - Blue	4.37		-----	89	99	104	108	74	54*
SOS - Blue	4.69			-----	84	113	94	58.5	78.5
Chirp - Blue	4.75				-----	101	107.5	65	103
3-color Chirp - Blue/Red-O/Cyan	4.79					-----	86	73.5	85
2 Hz 25% Duty - Blue	4.89						-----	72	101
2 Hz 50% Duty - Blue	5.55							-----	104
4 Hz Grp Interrupt - Red	5.59								-----
N = 21	☐ not significant		☐ p<.10		☐ p<.05*	☐ p<.01**			

- With the drop in signal intensity, the mean RTs to all signals were longer than in Test 2 Part 1.
- The mean percent correct dropped slightly for all but one signal (the 4 Hz alternating-color) with the percent correct ranging from 94-100% correct. But, as in Part 1, there were no cases where a subject failed to respond to any of the signals.
- The Wilcoxon analysis (Table 20) indicates significantly longer RTs to the 4 Hz Red and 2 Hz 50% duty cycle signals, indicating they were less conspicuous than some of the other signals.
- There was no statistical difference among the five signals with the fastest RTs. These more conspicuous signals were: 4 Hz group-alternating-color, 6 Hz, SOS, blue Chirp, and 3-color Chirp. Due to their faster response times, the project team chose the first three of these signals for further evaluation and comparison in Test 3.

6.7.3 Test 3 – Compare signals with pyrotechnic flare and COTS – Wednesday 17 Sep 2014

After Test 2, in conjunction with the on-site representative of the Coast Guard Headquarters Office of Design and Engineering Standards, the project manager decided to categorically exclude the color blue from further evaluation. 33 CFR 88.05 authorizes a "flashing blue light" for law enforcement vessels "when engaged in direct law enforcement or public safety activities." The project manager and sponsor representative decided a blue distress signal could run counter to 33 CFR 83.36 provisions that state "If necessary to attract the attention of another vessel, any vessel may make light or sound signals that cannot be mistaken for any signal authorized elsewhere in these Rules…" The on-site discussion continued to rationalize that since a blue flashing light already has a distinct meaning and purpose, particularly in "inland" waters, any effort to include a new scope for a blue flashing light could only lead to confusion. A telling scenario could entail multiple law enforcement vessels, flashing blue lights activated, conducting a search for a blue flashing distress signal.

Because of the similarity of the response times between cyan and blue, the project team decided for the remainder of the field testing to use cyan instead of blue.

Test 3 compared the three signals with best response times from Test 2 (allowing for the substitution of cyan for blue) to a red hand-held flare meeting the requirements of 46 CFR 160.021 (500 cd), and two, commercial off-the-shelf (COTS) devices, one with a 2Hz flashing white signal, and the other with a fluctuating 2-6Hz flickering red signal. Table 21 lists test signals for Test 3.

This test again experienced difficulty with observers identifying the test signals at 5-1/2 miles, so test signal distances are 5-4.7 NM from the observers. The east signal vessel position data recorder failed for a second time, so for the East signal vessel, positions during the tests are from the vessel's navigational equipment and test director logs.

Table 21. Test 3, Test signals.

Pattern	Color	Nominal Intensity	# Trials
4 Hz Group Alternating	Cyan/ Red-Orange	100 cd	6
6 Hz 50% Duty Cycle	Red-Orange	100 cd	6
6 Hz 50% Duty Cycle	Cyan	100 cd	6
SOS-Mod	Cyan	100 cd	6
Flare	Red	500 cd	6
COTS 1	White	100 cd	6
COTS 2	Red	100 cd	6
4 Hz Group Interrupt	Red	100 cd	6
No Signal	-	-	16

Table 22. Test 3, Results summary (20 Subjects).

Test 3 - Comparison with flare and COTS devices; by % Correct and Mean Response Time (RT) (seconds)									
Signal	Color	**Mean Correct**	Mean RT	No Response	Signal	Color	Mean Correct	**Mean RT**	No Response
4Hz Group Alt	Cyan/Red-Or	**0.97**	5.08	4%	4Hz Group Alt	Cyan/Red-Or	0.97	**5.08**	4%
6Hz 50% Duty Cycle	Red-Orange	**0.96**	6.16	5%	6Hz 50% Duty Cycle	Red-Orange	0.96	**6.16**	5%
4Hz 50% Duty Cycle	Red	**0.96**	6.39	5%	SOS	Cyan	0.92	**6.22**	4%
SOS	Cyan	**0.92**	6.22	4%	6Hz 50% Duty Cycle	Cyan	0.74	**6.34**	4%
Flare	Red	**0.79**	7.82	6%	4Hz 50% Duty Cycle	Red	0.96	**6.39**	5%
6Hz 50% Duty Cycle	Cyan	**0.74**	6.34	4%	Flare	Red	0.79	**7.82**	6%
COTS 2	Red	**0.70**	11.62	4%	COTS 2	Red	0.70	**11.62**	4%
COTS 1	White	**0.20**	14.77	8%	COTS 1	White	0.20	**14.77**	8%

The results summary (Table 22) provides mean percent correct and mean response time data. Because of the greater variability in both the RTs and in the percent correct data, the report provides statistical analyses on both data sets: comparison of percent correct in Table 23, comparison of RTs in Table 22

Table 23. Test 3, Wilcoxon analysis for percent correct.

Test 3 - Wilcoxon Analysis - Accuracy (% correct) Statisitical Comparison									
Signals	**% Correct**	4 Hz Alt Cyan/Red-O	6 Hz Red-Orange	SOS Cyan	6 Hz Cyan	4 Hz Gru Int Red	Flare	COTS 2	COTS 1
4 Hz Alt - Cyan/Red-Orange	97%	-----	8	ns	0**	ns	1**	0**	0**
6 Hz - Red-Orange	96%		-----	7	1**	ns	1**	1**	0**
SOS - Cyan	92%			-----	3**	ns	17*	6**	0**
6 Hz - Cyan	74%				-----	0**	36.5	82	2**
4 Hz Group Interrupt - Red	96%					-----	10.5**	0**	0**
Flare	79%						-----	33	0**
COTS 2	70%							-----	1**
COTS 1	20%								-----
N varied 3 to 19	☐ not significant		☐ p<.10		☐ p<.05*	☐ p<.01**			

- Subjects gave the highest correct response (97%) and the shortest mean RT (5.08 sec) to the 4 Hz Group Alternating-color signal. The RTs to this signal were statistically faster than the RTs to all but one of the other signals.
- Subjects responded well (92%-96% correct responses), with relatively good RTs (6.16 – 6.39 sec) to three other signals – 6 Hz Red-Orange, SOS Cyan, and 4 Hz Red. The percent correct responses to these three, plus the 4 Hz Alternating-Color signal, were significantly higher than for the remaining four signals.
- Subject response to the COTS 1 (white), the COTS 2 (red), and the flare yielded the lowest percent correct data (20% - 79% correct responses) and the slowest RTs (7.82 – 14.77 sec). The percent correct responses to these three signals were statistically lower than the to the four signals mentioned above, while the response times to the flare and COTS 2 were significantly slower than the response times to the four above-mentioned signals. The number of correct responses to COTS 1 was so low that it couldn't be included in the statistical test of response times.

Table 24. Test 3, Wilcoxon analysis for response time.

Test 3 - Wilcoxon Analysis - Response time (RT) Statisitical Comparison								
Signals	**Avg RT**	4 Hz Alt Cyan/Red-	6 Hz Red-Orange	SOS Cyan	6 Hz Cyan	4 Hz Int. Red	Flare	COTS 2
4 Hz Alt - Cyan/Red-Orange	5.08	-----	32**	35**	53	43*	25.5**	0**
6 Hz - Red-Orange	6.16		-----	105	88	93	42*	0**
SOS - Cyan	6.22			-----	99	96	48*	0**
6 Hz - Cyan	6.34				-----	97	35**	0**
4 Hz Grp Interrupt -	6.39					-----	50*	1**
Flare	7.82						-----	21.5**
COTS 2	11.62							-----
N=20 (19, 2 cells)	☐ not significant		☐ p<.10		☐ p<.05*	☐ p<.01**		
Note: COTS 1 RT was 14.77 sec; but because it had such a low % correct (19%), it couldn't be used for statistical analysis.								

Based on the percent correct and response times experienced in Test 3, the analyses point to significant differences in conspicuity among signals.

6.7.4 Test 4 – Continue comparison to COTS, adding a lower-intensity version of the "best-performing" signal – Thursday 18 Sep 2014

The project team used Test 4 to acquire additional data on the same signals from Test 3, but substituting a lower-intensity intensity 4Hz alternating cyan/red-orange for the handheld flare (Table 25). This substitution allowed the experimenters to evaluate whether a signal of less than 100 cd intensity would be conspicuous, or whether the 100 cd intensity should serve as a minimum. An additional benefit of this reevaluation was that for the first half of test 4, the signal vessels were visible at the planned 6 NM.

Table 25. Test 4, Test signals.

Pattern	Color	Nominal Intensity	# Trials
4 Hz Group Alternating	Cyan/ Red-Orange	100 cd	6
6 Hz 50% Duty Cycle	Red-Orange	100 cd	6
6 Hz 50% Duty Cycle	Cyan	100 cd	6
SOS-Mod	Cyan	100 cd	6
4 Hz Group Alternating	Cyan/ Red-Orange	80 cd	6
COTS 1	White	100 cd	6
COTS 2	Red	100 cd	6
4 Hz Group Interrupt	Red	100 cd	6
No Signal	-	-	16

Table 26. Test 4, Part 1 - Results summary (15 Subjects).

Test 4 Part 1 - Comparison with flare & COTS devices; by % Correct and Mean Response Time (RT) (seconds)									
Signal	Color	**Mean Correct**	Mean RT	No Response	Signal	Color	Mean Correct	**Mean RT**	No Response
4Hz Group Alt - 100 cd	Cyan/Red-Or	**100%**	5.02	2%	4Hz Group Alt - 100 cd	Cyan/Red-Or	100%	**5.02**	2%
SOS	Cyan	**93%**	6.68	5%	6Hz 50% Duty Cycle	Red-Orange	86%	**6.41**	7%
4Hz 50% Duty Cycle	Red	**89%**	7.68	7%	SOS	Cyan	93%	**6.68**	5%
6Hz 50% Duty Cycle	Red-Orange	**86%**	6.41	7%	6Hz 50% Duty Cycle	Cyan	79%	**6.98**	14%
4Hz Group Alt - 80 cd	Cyan/Red-Or	**80%**	10.94	10%	4Hz 50% Duty Cycle	Red	89%	**7.68**	7%
6Hz 50% Duty Cycle	Cyan	**79%**	6.98	14%	COTS 2	Red	79%	**8.93**	10%
COTS 2	Red	**79%**	8.93	10%	4Hz Group Alt - 80 cd	Cyan/Red-Or	80%	**10.94**	10%
COTS 1	White	**77%**	13.61	24%	COTS 1	White	77%	**13.61**	24%

Table 27. Test 4, Part 2 - Results summary (14 Subjects).

Test 4 Part 2 - Comparison with flare & COTS devices; by % Correct and Mean Response Time (RT) (seconds)									
Signal	Color	**Mean Correct**	Mean RT	No Response	Signal	Color	Mean Correct	**Mean RT**	No Response
6Hz 50% Duty Cycle	Red-Orange	**83%**	6.47	7%	SOS	Cyan	71%	**4.44**	10%
4Hz Group Alt - 100 cd	Cyan/Red-Or	**75%**	7.57	14%	6Hz 50% Duty Cycle	Red-Orange	83%	**6.47**	7%
SOS	Cyan	**71%**	4.44	10%	4Hz 50% Duty Cycle	Red	63%	**6.75**	7%
4Hz Group Alt - 80 cd	Cyan/Red-Or	**71%**	7.01	7%	4Hz Group Alt - 80 cd	Cyan/Red-Or	71%	**7.01**	7%
4Hz 50% Duty Cycle	Red	**63%**	6.75	7%	4Hz Group Alt - 100 cd	Cyan/Red-Or	75%	**7.57**	14%
6Hz 50% Duty Cycle	Cyan	**52%**	12.41	7%	COTS 1	White	10%	**12.03**	5%
COTS 2	Red	**26%**	18.24	5%	6Hz 50% Duty Cycle	Cyan	52%	**12.41**	7%
COTS 1	White	**10%**	12.03	5%	COTS 2	Red	26%	**18.24**	5%

In Test 4, a noticeable change in environmental conditions occurred between the first part and the second part of trials. For the first part, subjects experienced conditions that allowed for stationing the signal vessels at 6 NM from Eatons Neck (the first opportunity in four nights). Mid-way through trials, as the subjects returned from break, local wind velocity increased to the point of creating minor disruption at the data collection and recording site. As trials restarted, the signals were no longer visible, and experiment coordinators began to move vessels closer to the observer location, until the test lead could definitely see a signal from both boats. Test 4 Part 2 began with signal boats at approximately 5.8 NM, but over the duration of Part 2, the test director continued to move vessels closer, until they were within 5.5 miles of the observers.

As the vision researchers on the team noticed peculiarities in subject responses during Test 4 Part 2, and in preliminary analysis noted that there were substantial differences in the percent correct between the two parts (especially where the average mean correct responses dropped from 85% in Part 1 to 57% in part 2), the project team decided to not include the Part 2 results in the in-depth analysis.

Table 26 includes Test 4 results, Part 1, while Table 27 contains Part 2 results. Fifteen people participated in Part 1. One person's data reflected an inordinately high number of "no responses" (on over half the trials); that person's data were dropped from the analysis. A second participant did not have any correct responses for two of the test signals; therefore, they did not have response time data for the two signals. Because the analysis used a "repeated measures" type of statistical test, any dataset lacking a mean response time for any signal could not be used in the analysis. That left 13 sets of data that for the RT analysis, and 14 sets of data for the percent correct analysis.

Note in Table 26 the large number of “no response” to signals. This is the highest of any test (or part of test) in the entire field study. These high “no response” values apply to the signals in Part 1 with the lowest mean correct responses: the two COTS signals and the 6 Hz cyan. In Part 2 (Table 27), the mean correct response for these 3 signals is much lower than in Part 1, even though the “no responses” are closer to study average. These relatively low numbers of correct responses do not permit a full-series, in-depth analysis for Part 2.

- In Part 1, subjects identified the 4 Hz 100 cd alternating-color signal on 100% of its trials and responded to it with the fastest mean RT – 5.02 seconds. Statistically, the RTs to this signal were significantly faster than to all but the 6 Hz Red-Orange.

- The next-best percent correct responses (93% - 86%) and mean RTs (6.41 – 7.68 sec) were to. 6 Hz Red-Orange, SOS Cyan, and 4 Hz Red.
- The mean RTs to the white COTS, red COTS, and 80 cd alternating-color signals were the slowest from 13.61 seconds to 8.93 seconds, respectively. Statistically, the RTs to the white COTS signal was significantly slower than the RTs to all four signals mentioned above; and the RTs to the red COTS signal and to the 80 cd 4 Hz alternating-color signals were significantly slower than the RTs to three of the four signals above (excluding 4 Hz Red).

Test 4 Part 1 statistical results for the percent correct data are in Table 28, while statistical results for response times are in Table 29. Overall, Test 4 results generally substantiate Test 3 results.

Table 28. Test 4, Part 1 - Wilcoxon analysis for percent correct.

Test 4, Part 1 - Wilcoxon Analysis - % Correct Statistical Comparison									
Signals	**% Correct**	4 Hz Alt 100cd C/RO	SOS Cyan	4 Hz Int. Red	6 Hz Red-Orange	4 Hz Alt 80cd C/RO	6 Hz Cyan	COTS 2	COTS 1
4 Hz Alt 100 cd Cyan/Red-Orange	100%	-----	ns	ns	0	0**	0**	0**	0**
SOS - Cyan	93%		-----	ns	4.5	9	5.5	0*	5
4 Hz Grp Interrupt Red	89%			-----	ns	5.5	4.5	ns	2.5
6 Hz Red-Orange	85%				-----	16	15	10	9
4 Hz Alt 80 cd Cyan/Red-Orange	80%					-----	22	7	21
6 Hz - Cyan	79%						-----	13	1.5
COTS 2	79%							-----	13.5
COTS 1	77%								-----
N varied 4 to 11	☐ not significant		☐ p<.10		☐ p<.05*	☐ p<.01**			

Table 29. Test 4, Part 1 - Wilcoxon analysis for response time.

Test 4, Part 1 - Wilcoxon Analysis Response Time (RT) Statisitical Comparison									
Signals	**Avg RT**	4 Hz Alt 100cd	6 Hz Red-Orange	SOS Cyan	6 Hz Cyan	4 Hz Int. Red	COTS 2	4 Hz Alt 80cd C/RO	COTS 1
4 Hz Alt 100 cd Cyan/Red-Orange	5.02	-----	28	3**	17*	17*	4**	6**	0**
6 Hz Red-Orange	6.41		-----	34	39	33	19	15*	10*
SOS - Cyan	6.68			-----	43	35	17*	10*	3**
6 Hz - Cyan	6.98				-----	31	17*	15*	4**
4 Hz Grp Interrupt Red	7.68					-----	25	22	12*
COTS 2	8.93						-----	27	11*
4 Hz Alt 80 cd Cyan/Red-Orange	10.94							-----	28
COTS 1	13.61								-----
N = 13	☐ not significant		☐ p<.10		☐ p<.05*	☐ p<.01**			

7 CONCLUSIONS

From the field study, the project draws two main conclusions concerning signal conspicuity: (1) signal intensity is extremely important, as indicated by increased response times and decreased correct identifications when nominal signal intensity decreased from 200 cd, to 100 cd, to 80 cd, but possibly more important (2) a unique signal characteristic, both in pattern and color, that stands out from background clutter, and is clearly identified as "something different" may have more of an impact than intensity alone. The telling information here is that the test subjects correctly identified the standard, steady burning 500 cd pyrotechnic flare only 79% of the time, while during the same test, subjects correctly identified the nominal 100 cd, 4Hz group-alternating color, cyan/red-orange signal 97% of the time.

With respect to the 100 cd, 4Hz group-alternating cyan/red-orange signal, subjects correctly responded to it 97-100% of the time, and subjects' response times were consistently faster to it than to all others (significantly faster than the RTs to almost all others, including the pyrotechnic flare, and the two COTS devices.)

The results from Tests 3 and 4 indicate that the 100 cd 4 Hz group-alternating-color cyan/red-orange signal is the most conspicuous of the signals tested.

In combining effects of both intensity and pattern, the mean RT to the 4 Hz alternating-color signal showed the smallest change among signals in Test 3 where the nominal signal intensity decreased from 200 cd to 100 cd. Given that if a signal is farther away, it will appear less intense to an observer. Hence, a signal that resulted in a relatively small change in RT when intensity decreased may have benefit in distress location. However, as results from Test 4 show, decreasing intensity to 80 cd caused significantly longer mean RTs.

On the surface, it appears that the project would recommend a "nominal 100 cd" signal for the minimum intensity. However, as Table 9 indicates, the actual intensities are somewhat different than the "nominal" values. The actual intensities of the red-orange signals were 129 cd and 139 cd. Because the 4 Hz alternating-color signal resulted in near-perfect detection (97% correct in Test 3, and 100% correct in Test 4, Part 1), the project chooses the lower intensity value, confident that it provides sufficient conspicuity (rounded it to 130 cd for convenience).

The cyan component of this signal had actual intensities of 121 cd and 112 cd. From the performance of the cyan S-O-S signal in Test 4, Part 1, we found that the higher-intensity cyan signal produced better response time and percent correct performance than did the lower-intensity cyan signal: the average RT for was 4.76 sec, compared to 7.97 sec for the 112 cd signal; also, the 121 cd signal produced 95% correct detection vs. 89% for the 112 cd signal. Because neither intensity for cyan produced 100% correct detections, the project recommends 130 cd as the minimum intensity for the cyan component.

Though the original goals of the experiment looked to establish a "range" of signal characteristics (color, pattern, and intensity), with the concurrence of the primary sponsor, the project reconsidered this target, and instead, focused on a much narrower description of a conspicuous visual distress signal, visible at 6 NM in 10 miles of meteorological visibility. This characteristic for this signal is defined as:

- Two colors: cyan and red-orange, in an alternating-color pattern, in groups of three to four flashes per group. (In the field tests, the cyan was four flashes, and the red-orange was three flashes.)

- A flash frequency of 4Hz, 50% duty cycle, with no more than 250 milliseconds between any groups of single-color flashes.
- A minimum effective intensity of ≥ 50 cd. This translates to an average intensity of ≥ 130cd per individual discernable flash.

The measures of conspicuity for this experiment, correct response and reaction time to a displayed signal, and the above conclusion addressing a conspicuous signal are strictly limited to the scenario posed to the field-study subjects described earlier, during nighttime, against sparse background lighting clutter. All subjects, with varying degrees of experience in government, commercial, or recreational vessel operation, conducting boating safety education and training, and performing distress response, were explicitly advised that a signal might appear, and the signal, if it appeared, would be in one of two limited arcs of visibility, with background lighting clutter that could either assist or impede in their signal identification. The subjects were all alerted to the possible signal before its activation. The project team does not infer, under any circumstances, that the most conspicuous signal described above will, on its own, serve as an alerting device.

This work strictly pertains to a visual signal (i.e., viewed by the unaided eye). Since U. S. Coast Guard rescue aircraft normally conduct nighttime searches using NVIS with "minus-blue" filtering," additional research and testing may lead to the inclusion, of an additional flashing signal, with signal wavelength closer to the NVIS central response range, approximately 750-800 nanometers

As defined, this signal meets both the International and Inland COLREGS Rule 36 requirement for "signals to attract attention," i.e., "light…signals that cannot be mistaken for any signal authorized elsewhere in the Rules," and in accordance with International Rule 36 "such that it cannot be mistaken for any aid to navigation."

The R&DC project team believes that it is well within reach (considering current off the shelf and developmental devices) to manufacture a signal device as described. As a matter of example, this report includes an Appendix C that discusses battery requirements for an LED Visual Distress Signal Device.

The characteristic for the "electric S-O-S distress light" defined in 46 CFR 161.013 is inadequate. During laboratory pilot testing, the project team almost immediately realized the shortcomings associated with prolonged eclipses ("off time") between letters and SOSs. The project team performed multiple iterations on the SOS signal before achieving a flash pattern that achieved a reasonable level of conspicuity.

8 RECOMMENDATIONS

The CG R&D Center Alternatives to Pyrotechnics Project recommends that the Coast Guard's Office of Design and Engineering Standards adopt the following characteristic for an LED Visual Distress Signal Device.

- Two colors: cyan and red-orange, in an alternating-color pattern, in groups of three to four flashes per group. (In the field tests, the cyan was four flashes, and the red-orange was three flashes.)
- A flash frequency of 4Hz, 50% duty cycle, with no more than 250 milliseconds between any groups of single-color flashes.
- A minimum effective intensity of ≥ 50 cd. This translates to an average intensity of ≥ 130cd per individual discernable flash.

Further, the project recommends particular attention to IALA Recommendation E-200-4 On Marine Signal Lights, Part 4 – Determination and Calculation of Effective Intensity, Edition 1, December 2008, and application of the guidance therein, particularly in the case of very-rapidly-repeating flashes that make up a discernible flash, and then calculating effective intensity of the discernible flash.

As the report clearly states the limitations of this project's effort, and as the conclusions emphasize how correct signal identification and response time account for conspicuity of the signal for distress location, the project recommends, that if adopted, the signal as described be considered an equivalent for a hand-held pyrotechnic flare as a nighttime distress signal.

The project recommends eliminating the present "electric S-O-S distress light" defined in 46 CFR 161.013.

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APPENDIX A. ELECTRIC DISTRESS LIGHTS FOR BOATS (46 CFR 161.013)

SOURCE: CGD 76–183a, 44 FR 73054, Dec. 17, 1979, unless otherwise noted.

§ 161.013–1 Applicability.

(a) This subpart establishes standards for electric distress lights for boats.

(b) [Reserved]

§ 161.013–3 General performance requirements.

(a) Each electric light must:

(1) Emit a white light which meets the intensity requirements of § 161.013–5;

(2) Be capable of automatic signaling in a manner which meets the requirements of § 161.013–7;

(3) Contain an independent power source which meets the requirements of § 161.013–9;

(4) Float in fresh water with the lens surface at or above the surface of the water;

(5) Be equipped with a waterproof switch; and

(6) Meet the requirement of paragraphs (a) (1) through (4) of this section after floating for at least 72 hours followed by submersion in 5% by weight sodium chloride solution for at least 2 hours.

§ 161.013–5 Intensity requirements.

(a) If an electric light emits light over an arc of the horizon of 360 degrees, the light must:

(1) When level, have a peak intensity within 0.1 degrees of the horizontal plane;

(2) Have a peak Equivalent Fixed Intensity of at least 75 cd; and,

(3) Have a minimum Equivalent Fixed Intensity within a vertical divergence of ±3 degrees of at least 15 cd.

(b) If an electric light emits a directional beam of light, the light must:

(1) Have an Equivalent Fixed Intensity of no less than 25 cd within ±4 degrees vertical and ±4 degrees horizontal divergence centered about the peak intensity; and,

(2) Have a minimum peak Equivalent Fixed Intensity of 2,500 cd.

(c) The Equivalent Fixed Intensity (EFI) is the intensity of the light corrected for the length of the flash and is determined by the formula: $EFI = I \times (t_c - t_i) / 0.2 + (t_c - t_i)$

Where:

I is the measured intensity of the fixed beam,

t_c is the contact closure time in seconds, (0.33 for this S-O-S signal), and

t_i is the incandescence time of the lamp in seconds.

(d) An electric light which meets the requirements of either paragraph (a) or (b) of this section need not, if capable of operating in both manners, meet the requirements of the other paragraph.

§ 161.013–7 Signal requirements.

(a) An electric light must have a flash characteristic of the International Morse Code for S-O-S and, under design conditions,

(1) Each short flash must have a duration of 1⁄3 second;

(2) Each long flash must have a duration of 1 second;

(3) The dark period between each short flash must have a duration of 1⁄3 second;

(4) The dark period between each long flash must have a duration of 1⁄3 second;

(5) The dark period between each letter must have a duration of 2 seconds;

(6) The dark period between each S-O-S signal must have a duration of 3 seconds.

(b) The flash characteristics described in paragraph (a) must be produced automatically when the signal is activated.

§ 161.013–9 Independent power source.

(a) Each independent power source must be capable of powering the light so that it meets the requirements of § 161.013–3(a)(1) and emits a recognizable flash characteristic of the International Morse Code for S-O-S at a rate of between 3 and 5 times per minute after six hours of continuous display of the signal.

(b) If the independent power source is rechargeable, it must have a waterproof recharger designed for marine use.

(c) If the independent power source requires external water to form an electrolyte, it must operate in sea water and fresh water.

§ 161.013–11 Prototype test.

(a) Each manufacturer must test a prototype light identical to the lights to be certified prior to the labeling required by § 161.013–13.

(b) If the prototype light fails to meet any of the general performance requirements of § 161.013–3 the lights must not be certified under this subpart.

(c) Each manufacturer must:

(1) Forward the test results within 30 days to the Commandant (CG–ENG), U. S. Coast Guard, 2100 2nd St., SW., Stop 7126, Washington, DC 20593–7126; and

(2) Retain records of the test results for at least 5 years, or as long as the light is manufactured and certified, whichever is longer.

§ 161.013–13 Manufacturer certification and labeling.

(a) Each electric light intended as a Night Visual Distress Signal required by 33 CFR part 175 must be certified by the manufacturer as complying with the requirements of this subpart.

(b) Each electric light must be legibly and indelibly marked with:

(1) Manufacturer's name;

(2) Replacement battery type;

(3) Lamp size; and

(4) The following words—''Night Visual Distress Signal for Boats Complies with U. S. Coast Guard Requirements in 46 CFR 161.013. For Emergency Use Only.''

(c) If an electric light is designed for use with dry cell batteries the label must advise the consumer on the battery replacement schedule which under normal conditions would maintain performance requirements of § 161.013–3.

§ 161.013–17 Manufacturer notification.

Each manufacturer certifying lights in accordance with the specifications of this subpart must send written notice to the Commandant (CG–ENG), U. S. Coast Guard, 2100 2nd St., SW., Stop 7126, Washington, DC 20593–7126 within 30 days after first certifying them, and send a new notice every five years thereafter as long as it certifies lights.

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APPENDIX B. ADDITIONAL FIELD TEST DATA

B.1 Test 1 – Monday 15 September 2014

Table B-1. Test 1, Signal distances.

			WEST BOAT - DISTANCES				EAST BOAT - DISTANCES			
	EDT	Event	Vsl Lat N	Vsl lon W	NM fm EaN	Mean Dist	Vsl Lat N	Vsl lon W	NM fm EaN	Mean Dist
TEST 1 - 15 Sep	2002	PRACTICE 1	41.050	73.356	6.2		41.045	73.447	5.9	
	2009	end practice 1	41.050	73.358	6.1	6.2	41.044	73.451	5.9	5.9
	2118	PRACTICE 2	41.022	73.389	4.2		41.027	73.436	4.7	
	2120		41.022	73.389	4.2		41.025	73.437	4.7	
	2129	end practice 2	41.023	73.390	4.2	4.2	41.027	73.436	4.7	4.7
	2130		41.023	73.390	4.2		41.027	73.436	4.7	
	2133	**TEST 1 PART 1**	41.022	73.390	4.2		41.027	73.435	4.7	
	2140		41.022	73.389	4.2		41.026	73.436	4.7	
	2150		41.022	73.387	4.2		41.026	73.435	4.7	
	2200		41.022	73.388	4.2		41.026	73.436	4.7	
	2210		41.022	73.388	4.2		41.026	73.435	4.7	
	2215	PART 1 END	41.022	73.388	4.2	4.2	41.027	73.436	4.7	4.7
	2237	**TEST 1 - PART 2**	41.021	73.386	4.1		41.025	73.436	4.6	
	2240		41.021	73.386	4.1		41.025	73.435	4.6	
	2250		41.022	73.389	4.2		41.026	73.436	4.7	
	2300		41.022	73.387	4.2		41.026	73.436	4.7	
	2310		41.022	73.388	4.1		41.027	73.435	4.7	
	2310	PART 2 END	41.022	73.388	4.1	4.2	41.028	73.435	4.7	4.7

Table B-2. Test 1, Environmental conditions.

		Buoy 44040 - Western LIS				Buoy ARTG				Eatons Neck
	EDT	Air Temp (deg F)	Surface Water Temp (deg F)	Relative Humidity (%)	Wind Spd (kts)	Air Temp (deg F)	Surface Water Temp (deg F)	Relative Humidity (%)	Wind Spd (kts)	Observed Visibility (NM)
TEST 1 - 15 Sep	20:00	65.1	71.5	60.1	10.4	65.8	71.9	60.4	10.1	>10
	20:15	65.0	71.5	61.5	9.0	65.9	71.9	60.3	10.4	>10
	20:30	64.9	71.4	62.6	7.8	65.8	71.9	62.3	9.5	>10
	20:45	65.0	71.4	62.5	8.9	65.7	71.8	63.7	8.7	>10
	21:00	64.8	71.4	63.3	8.7	65.4	71.7	63.6	8.6	>10
	21:15	64.7	71.4	64.3	8.2	65.4	71.7	64.8	9.4	>10
	21:30	64.6	71.3	64.5	7.4	65.4	71.8	64.6	9.1	>10
	21:45	64.8	71.3	66.1	6.6	65.2	71.7	64.6	7.8	>10
	22:00	64.5	71.3	66.3	6.8	65.2	71.7	64.6	7.8	>10
	22:15	64.4	71.3	66.6	7.1	65.1	71.8	66.2	6.2	>10
	22:30	64.3	71.2	66.6	6.4	65.3	71.7	64.4	7.4	>10
	22:45	64.4	71.2	67.7	6.0	65.5	71.8	63.9	7.8	>10
	23:00	64.4	71.2	68.9	6.0	65.7	71.7	63.6	8.4	>10
	23:15	64.5	71.2	69.2	6.6	65.7	71.8	64.7	7.7	>10

B.2 Test 2 – Tuesday 16 September 2014

Table B-3. Test 2, Signal distances.

			WEST BOAT - DISTANCES				EAST BOAT - DISTANCES			
	EDT	**TEST 2**	**Vsl Lat**	**Vsl lon**	**NM fm EaN**		**Vsl Lat**	**Vsl lon**	**NM fm EaN**	
TEST 2 - 16 Sep	2002	Practice start	41.037	73.475	6.1		41.049	73.355	6.1	
	2007	Practice End	41.035	73.474	6.0	6	41.049	73.357	6.1	6.1
	2029	Practice-restart	41.023	73.454	4.9		41.038	73.386	5.1	
	2030		41.023	73.454	4.9		41.038	73.386	5.1	
	2040		41.023	73.452	4.8		41.037	73.387	5.1	
	2040	Practice End	41.023	73.452	4.8	4.8	41.037	73.387	5.1	5.1
	2044	**TEST 2 PART 1**	41.023	73.455	4.9		41.037	73.387	5.1	
	2050		41.023	73.455	4.9		41.037	73.387	5.1	
	2100		41.023	73.451	4.8		41.036	73.386	5.0	
	2110		41.023	73.451	4.8		41.035	73.385	5.0	
	2117	PART 1-END	41.023	73.450	4.7	4.8	41.037	73.386	5.1	5.0
	2140	**TEST 2-PART 2**	41.023	73.449	4.7		41.037	73.385	5.1	
	2150		41.022	73.448	4.7		41.037	73.385	5.1	5.1
	2200		41.022	73.450	4.7					
	2210		41.022	73.448	4.7		Estimated		5.0	
	2210	PART 2 END	41.022	73.448	4.7	4.7				

Table B-4. Test 2, Environmental conditions.

		Buoy 44040 - Western LIS				Buoy ARTG				Eatons Neck
	EDT	Air Temp (deg F)	Surface Water Temp (deg F)	Relative Humidity (%)	Wind Spd (kts)	Air Temp (deg F)	Surface Water Temp (deg F)	Relative Humidity (%)	Wind Spd (kts)	Observed Visibility (NM)
TEST 2 - 16 Sep	20:00	67.1	70.9	69.5	4.6	67.4	71.1	64.6	5.4	>10
	20:15	66.8	70.9	71.0	4.2	67.4	71.1	65.9	6.4	>10
	20:30	66.4	70.9	72.8	4.6	67.3	71.0	68.1	7.8	>10
	20:45	66.1	70.8	71.9	5.6	67.0	71.0	67.6	8.5	>10
	21:00	66.1	70.9	71.9	6.6	67.0	71.0	67.9	9.1	>10
	21:15	65.9	70.8	71.9	6.3	66.7	71.0	69.1	8.1	>10
	21:30	65.5	70.8	75.0	7.0	66.6	71.0	68.9	7.6	>10
	21:45	65.6	70.8	75.5	6.7	66.6	71.0	69.6	7.1	>10
	22:00	65.2	70.8	70.8	7.3	66.4	71.1	69.5	6.8	>10
	22:15	65.2	70.8	70.0	6.3	66.4	71.0	71.1	7.8	>10
	22:30	64.6	70.8	73.6	6.0	66.1	71.0	69.7	8.0	>10

B.3 Test 3 – Wednesday 17 September 2014

Table B-5. Test 3, Signal distances.

	EDT	TEST 3	Vsl Lat	Vsl lon	NM fm EaN				NM fm EaN	
TEST 3 - 17 Sep	1956	Practice start	41.027	73.470	5.5			Estimated	5.3	
	2000		41.027	73.471	5.5					
	2010		41.027	73.470	5.5					
	2015	Practice End	41.027	73.469	5.5	5.5		Estimated	5.1	
	2039	**TEST 3-PART 1**	41.021	73.458	4.9			Estimated	5.0	
	2040		41.021	73.458	4.9					
	2050		41.019	73.457	4.7			Estimated	4.9	
	2100		41.019	73.456	4.7					
	2110		41.020	73.456	4.8					
	2120		41.019	73.453	4.6					
	2127	PART 1 END	41.019	73.452	4.6	4.7		Estimated	4.7	
	2156	**TEST 3-PART 2**	41.024	73.444	4.7					
	2200		41.025	73.443	4.7					
	2210		41.025	73.444	4.8					
	2220		41.026	73.443	4.8					
	2227	PART 2 END	41.026	73.444	4.8	4.8				

Table B-6. Test 3, Environmental conditions.

		Buoy 44040 - Western LIS				Buoy ARTG				Eatons Neck
	EDT	Air Temp (deg F)	Surface Water Temp (deg F)	Relative Humidity (%)	Wind Spd (kts)	Air Temp (deg F)	Surface Water Temp (deg F)	Relative Humidity (%)	Wind Spd (kts)	Observed Visibility (NM)
TEST 3 - 17 Sep	20:00	66.5	71.8	60.7	7.2	66.8	71.8	59.1	8.5	>10
	20:15	66.0	71.8	60.6	7.4	66.8	71.7	61.0	8.1	>10
	20:30	65.9	71.6	62.2	7.8	66.8	71.5	61.0	7.6	>10
	20:45	65.9	71.6	64.1	8.3	66.7	71.5	62.2	8.7	>10
	21:00	65.8	71.6	64.9	8.6	66.3	71.5	63.6	8.0	>10
	21:15	65.7	71.5	65.0	8.9	66.2	71.5	65.2	7.7	>10
	21:30	65.6	71.5	65.2	8.9	66.4	71.5	65.7	7.8	>10
	21:45	65.4	71.4	66.5	7.9	66.7	71.4	63.4	9.1	>10
	22:00	65.0	71.5	67.2	7.6	66.9	71.3	63.0	9.1	>10
	22:15	65.0	71.5	68.2	7.0	66.8	71.4	62.7	9.3	>10
	22:30	65.0	71.5	68.5	6.7	66.7	71.4	62.8	9.0	>10

B.4 Test 4 – Thursday 18 September 2014

Table B-7. Test 4, Signal distances.

	EDT	TEST 4	Vsl Lat	Vsl lon	NM fm EaN		Vsl Lat	Vsl lon	NM fm EaN	
TEST 4 - 18 Sep	2009	Practice start	41.045	73.459	6.1		41.054	73.379	6.2	
	2021	Practice-restart	41.044	73.458	6.1		41.054	73.380	6.1	
	2033	Practice End	41.044	73.459	6.1	6.1	41.053	73.383	6.1	6.1
	2036	**TEST 4-PART 1**	41.044	73.459	6.1		41.053	73.383	6.1	
	2040		41.044	73.459	6.1		41.053	73.383	6.1	
	2050		41.046	73.457	6.2		41.053	73.382	6.1	
	2100		41.046	73.457	6.2		41.053	73.382	6.1	
	2110		41.046	73.457	6.2		41.053	73.382	6.1	
	2115	PART 1 END	41.045	73.458	6.2	6.1	41.053	73.382	6.1	6.1
	2130	**TEST 2-PART 2**	41.045	73.456	6.1		41.053	73.381	6.1	
	2139	Part 2-Pause	41.044	73.457	6.1	6.1	41.054	73.383	6.1	6.1
	2151	**PART2-RESTART**	41.041	73.456	5.9		41.048	73.384	5.8	
	2200		41.039	73.454	5.7		41.047	73.382	5.7	
	2210		41.038	73.453	5.7		41.044	73.383	5.5	
	2220		41.034	73.452	5.4		41.043	73.382	5.5	
	2230		41.033	73.450	5.3		41.042	73.382	5.4	
	2232	PART 2-END	41.033	73.450	5.3	5.6	41.041	73.382	5.4	5.5

Table B-8. Test 4, Environmental conditions.

		Buoy 44040 - Western LIS				**Buoy ARTG**				**Eatons Neck**
	EDT	Air Temp (deg F)	Surface Water Temp (deg F)	Relative Humidity (%)	Wind Spd (kts)	Air Temp (deg F)	Surface Water Temp (deg F)	Relative Humidity (%)	Wind Spd (kts)	Observed Visibility (NM)
TEST 4 - 18 Sep	20:00	69.3	72.0	59.2	4.5	70.9	71.6	54.0	5.1	>10
	20:15	68.2	72.1	64.8	3.1	70.2	71.5	59.2	6.1	>10
	20:30	68.2	72.1	63.6	3.4	69.6	71.5	56.9	8.5	>10
	20:45	67.7	72.1	62.7	5.0	68.9	71.5	61.9	9.2	>10
	21:00	67.1	72.1	62.0	5.0	68.6	71.5	60.2	10.8	>10
	21:15	66.5	72.0	63.4	5.7	68.2	71.3	60.6	12.0	>10
	21:30	65.5	71.9	63.6	7.0	67.7	71.2	61.8	13.8	>10
	21:45	64.9	71.8	63.9	8.1	67.1	71.2	64.6	15.4	>10
	22:00	64.5	71.7	64.8	8.5	66.6	71.3	65.4	14.8	>10
	22:15	64.6	71.6	65.2	10.3	66.4	71.2	65.4	14.6	>10
	22:30	64.8	71.5	65.5	11.7	66.2	71.2	64.6	15.7	>10
	22:45	64.5	71.5	65.2	12.4	65.9	71.2	64.8	15.3	>10

APPENDIX C. BATTERY REQUIREMENTS FOR AN LED VISUAL DISTRESS SIGNAL DEVICE (VDSD)

Two criteria determine the battery requirements of an LED driven VDSD: luminous intensity and run time. Intensity determines power requirements (watts), and runtime determines energy requirements (watt hours). A battery typically is rated in amp hours or watt hours. Therefore, in order to specify a battery for the device, the power necessary to produce the desired luminous intensity needs to be calculated. Once the power requirement (watts) is know the battery capacity needed is calculated by multiplying watts x run time to get watt hours. The following is an example of the calculations one needs to specify a battery for a hypothetical VDSD.

The hypothetical VDSD signal will be 4Hz continuous flash, cyan in color, 50% duty cycle with an effective intensity of 50 candela (cd) and desired runtime of 4 hours, radiating in a hemispherical pattern.

Per Blondel-Rey, the actual intensity the VDSD must produce for an effective intensity of 50cd is 130cd.

To produce uniform hemispherical light signal of 130 cd in all directions, use the following assumption: the LED emitter or an array of LED emitters produce a uniform hemispherical radiation pattern exhibiting a luminous intensity of 130cd. This may seem obvious, but in practice could be challenging to achieve.

LED emitters are specified in lumens, the signal requirement is in cd. Candela = lumens per steradian. A steradian is a solid angle depicting an area on the surface of a sphere equal to the radius of the sphere squared. A sphere measures 4π steradian and a hemisphere measures 2π steradian.

Since candela = lumens per steradian we need to multiply the desired luminous intensity (candela) x 2π to get the total lumen the LED's must emit to radiate130 cd in uniform hemispherical pattern. I.e.,

2π x 130 lumen = 817 lumen

The luminous efficacy of an LED is a measure of = lumens/watt. A typical cyan LED (in 2014) has a luminous efficacy of 56 lumens/watt. Dividing the required lumen by the luminous efficacy of the LED yields the power draw of the LED during the flash.

Flash power draw = 817 lumen   56 lumen/watt = 14.6 watts

In this example the duty cycle of the signal is 50%. Therefore, since the LED is only on 50% of the time, the average power for this signal will be one half the power draw during the flash:

Average power draw = 0.5 x 14.6 watts = 7.3 watts.

In this example, the run time is 4 hours. The total energy required for the signal would then be the average power draw multiplied by the run time.

Total Energy = 7.3 watts x 4hr = 29 watt-hr

The signal will need a battery with a capacity of 29 watt hours.

As stated, batteries are rated either in watt hours or amp hours (Ah). Watt hours are simply the amp hour capacity of a battery multiplied by the battery voltage (i.e. a 3 volt, 5Ah battery has a 15 watt hour capacity; two 3V, 5Ah batteries have a 30 watt hour capacity). Battery capacity specifications vary among manufacturers. Carefully examine battery discharge curves before determining battery types and sizes before battery selection.

As an example, one make and model of 3V battery has a 5Ah rating. Two of this type battery provide 30 watt hours. Allowing for a safety factor, the signal in this example would most likely take 3 batteries to guarantee operation for 4 hours.

A second make and model of C-sized lithium battery rates 3.6 V at 7.7 Ah (for almost 28 watt-hours). Though close to the total energy requirement, allowing for a safety factor, again might yield a device with two of this type battery.